NASA CR-72432

LIQUID HYDROGEN POSITIVE EXPULSION BLADDERS

by

Karl E. Wiedekamp

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lewis Research Center

Contract NAS 3-11192

THE BOEING COMPANY

NOTICE

Requests for copies of this report should be referred to:

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Attention: AFSS-A
Washington, D. C. 20546

NASA CR-72432

FINAL REPORT

LIQUID HYDROGEN POSITIVE EXPULSION BLADDERS

by
Karl E. Wiedekamp

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center

May, 1968

CONTRACT NAS 3-11192

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Liquid Rocket Technology Branch
Chemical Rocket Division
R. F. Lark

THE BOEING COMPANY
Aerospace Group
Missile & Information Systems Division
Seattle, Washington

FOREWORD

This report was prepared by The Boeing Company, under NASA Contract NAS 3-11192. The work was administered by the Lewis Research Center, Chemical Rocket Division, Cleveland, Ohio with Mr. Raymond F. Lark as program manager.

Performance of this contract was under the direction of the Materials Research and Development Organization, Missile Structures and Materials Technology, Missile and Information Systems Division of The Boeing Company. Mr. P. B. Kennedy was Program Supervisor and Mr. K. E. Wiedekamp Program Manager. Liquid hydrogen expulsion testing was conducted by Mr. C. C. Mahnken. Sea-Space Systems, Inc. fabricated the test bladders with Mr. J. C. Lair as program engineer.

Contributions by Mr. H. M. Olden and Mr. A. D. Von Volkli to the program and in the preparation of this report are gratefully acknowledged.

LIQUID HYDROGEN POSITIVE EXPULSION BLADDERS

by
Karl E. Wiedekamp

ABSTRACT

Liquid hydrogen expulsion tests were performed using multi-ply bladders fabricated from Mylar, Kapton and an experimental polyester film. The effects of the outward expulsion mode and of an integral collapse control device on hydrogen diffusion and cyclic expulsion endurance were determined. Two bladders were able to complete 25 expulsion cycles, although interply inflation and some gas leakage was noted in all bladders tested.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIQUID HYDROGEN POSITIVE EXPULSION BLADDERS

by
Karl E. Wiedekamp
THE BOEING COMPANY

1.0 SUMMARY

The program was a two phase effort for the fabrication and evaluation of multiple ply polymeric film bladders for the expulsion of liquid hydrogen. TASK I consisted of the fabrication of seven test bladders, one of Kapton/Nomex and two each of Mylar, Mylar/MERFAB, and No. 3711 Film/Nomex. One bladder of each type contained a collapse control device as an integral part of the bladder.

TASK II of the program was to experimentally determine the following factors for liquid hydrogen positive expulsion bladders:

1. Evaluate the outward expulsion mode, liquid hydrogen external to the bladder, as it affects hydrogen diffusion into the bladder and the cyclic endurance of the bladder.

2. Compare the performance of polymeric bladders with barrier plies of Mylar, Kapton and No. 3711 film.

3. Determine the effectiveness of controlled collapse patterns on the cyclic endurance of the bladders.

The amount and effect of hydrogen diffusion into the bladders was determined for one bladder of each type by maintaining a half-expanded bladder at -423°F for 24 hours with zero pressure differential across the bladder. The test on the No. 3711 film bladder was terminated after 12 hours due to an unexplained difficulty in maintaining the required zero pressure differential. In all of the bladders the helium gas in the interior of the bladder contained a significant

percentage of hydrogen gas at the end of the test period, but it was not possible to ascertain whether this was due to permeation of the hydrogen through the barrier plies or leakage in the stem attachment. All of the bladders showed some degree of inter-ply inflation after the diffusion test. In the Kapton/Nomex bladder, the inter-ply inflation was due to helium gas and was so severe that the bladder could not be collapsed to fill the dewar with liquid hydrogen for the cyclic expulsion tests.

One Mylar and one No. 3711 film/Nomex bladder, both with collapse control devices, completed the 25 expulsion cycle goal of the program. The -423°F helium porosity rates at the completion of the 25 cycles were 412.8 cc/min and 187.6 cc/min, respectively. The companion bladders for these two, without collapse control devices, failed after 10 expulsion cycles with -423°F helium porosity rates of greater than 4500 cc/min for the Mylar and greater than 570 cc/min for the No. 3711 film/Nomex.

Neither of the Mylar/MERFAB bladders performed very well. The bladder without the collapse control device failed on the first expulsion cycle attempted. The one with the collapse control device failed after ten cycles with a -423°F helium porosity rate of greater than 4320 cc/min. The principle cause for failure for these bladders was a residual tackiness of the adhesive on the MERFAB plies which prevented the movement between the plies required to equalize the pressure loads and thus caused failure of the weak Mylar plies.

The major conclusions derived from this program were:

1. In regard to inter-ply inflation and cyclic endurance, the outward expulsion mode of bladder operation offers no advantage over the inward expulsion mode.

2. Helium and hydrogen gas permeation through the barrier plies must be controlled before reliable bladders can be developed for liquid hydrogen expulsion.

3. From the standpoint of resistance to fracture, tearing and puncture the No. 3711 film was the best barrier film material tested. Kapton was second and Mylar last.

4. The collapse control device, although not of optimum design, increased the cyclic endurance of the bladders tested.

2.0 INTRODUCTION

The advantages and practicality of propellant transfer through the use of a light-weight expulsion bladder have been verified to a great extent for storable propellants. The development of equally reliable and light-weight expulsion bladders for cryogenic propellants for use in space offers even more advantages than bladders for storable propellant since the existing cryogenic systems utilize heavy high-pressure super-critical tankage, pumps and valves. In applications such as reaction control systems, multiple engine restarts, orbiting vehicle refueling and replenishment of life support systems, an expulsion bladder system offers great weight and space savings.

Metallic bellows and diaphragms have proven capable of repeated cycles at cryogenic temperatures, but these incur weight and volumetric efficiency penalties as well as shape limitations. Metallic bladders do not withstand repeated folding, particularly three-corner folding, without pinholing or tearing.

The feasibility of polymeric expulsion bladders for liquid nitrogen (-320°F) and liquid oxygen (-297°F) has been demonstrated under NASA LeRC contracts (References 1 and 2). An investigation of polymeric expulsion bladders for liquid hydrogen under NASA LeRC Contract NAS 3-6288 indicated some degree of promise from bladders of Mylar and Kapton films at this more severe operating temperature of -423°F (Reference 3). In addition to these contracted investigations, NASA LeRC has conducted in-house studies of polymeric film properties at -423°F. One of these studies indicated that certain experimental polyester films, such as No. 3711, were more resistant to tearing and cracking when flexed at -423°F than the commercially available polyester film, Mylar.

The objectives of this program were to experimentally determine the following factors for liquid hydrogen positive expulsion bladders:

1. Evaluate the outward expulsion mode, liquid hydrogen external to the bladder, as it effects hydrogen diffusion into the bladder, and the cyclic endurance of the bladder.

2. Compare the performance of polymeric bladders with barrier plies of Mylar, Kapton and No. 3711 film.

3. Determine the effectiveness of controlled collapse patterns on the cyclic endurance of the bladders.

Seven bladders, with constructions as shown in Section 3, Table 1, were tested to determine these factors.

3.0 TASK I - BLADDER FABRICATION

All bladder fabrication was performed by Sea-Space Systems, Inc. to a process specification developed by Sea-Space Systems, Inc. and approved by The Boeing Company. Material and configuration control was provided by a letter specification from The Boeing Company.

3.1 MATERIALS

The following end-item materials were used for bladder fabrication.

a. 0.25 mil Mylar C. film

b. 0.50 mil Kapton film

c. 2.0 mil Nomex paper

d. 5.0 mil Kapton film

e. 0.50 mil Experimental film No. 3711

f. 0.60 mil MERFAB (reinforced polyethylene film)

g. S-110 adhesive

h. 0.125 inch diameter half-round polyurethane rod

i. Bostik 4034 adhesive

Materials (a) through (d) are products of E. I. du Pont de Nemours and Company. Material (e) is an experimental polyester film supplied through NASA LeRC. MERFAB and S-110 adhesive are proprietary products of Sea-Space Systems, Inc. The polyurethane rod was molded by The Boeing Company from Adiprene L-100 and MOCA from E. I. du Pont de Nemours and Company. Bostik 4034 is a rubber-base adhesive from United Shoe Machinery Corporation.

The Boeing Company conducted a short evaluation of the processing characteristics of the No. 3711 film. An attempt was made to fabricate lap bonds with the film using an adhesive commonly used for cryogenic bladders, G.T.-100 from G. T. Schjeldahl Company. The film proved to be incompatible with the 280°F to 340°F processing temperature required for the adhesive. Further tests showed that the maximum bonding temperature that could be used on No. 3711 film without causing extensive shrinking and wrinkling of the bond area was 170°F. It was also observed that chlorinated solvents caused a similar wrinkling or dissolved the film. After an evaluation of five adhesives which were immediately available to The Boeing Company, Bostik 4034 was selected as being the most compatible with the film and the bladder fabrication procedures. This adhesive which yielded 0.50 inch lap bonds with 180° peel strengths greater than the tensile strength of the film at room temperature and -320°F was proposed as a substitute for S-110, if required. Sea-Space Systems, Inc. subsequently reported that Bostik 4034 formed too thick an adhesive layer for satisfactory bladder fabrication and that S-110 adhesive was compatible with No. 3711 film. The Bostik 4034 adhesive was therefore used only to fabricate the Nomex substrate plies and to seal the stem assembly.

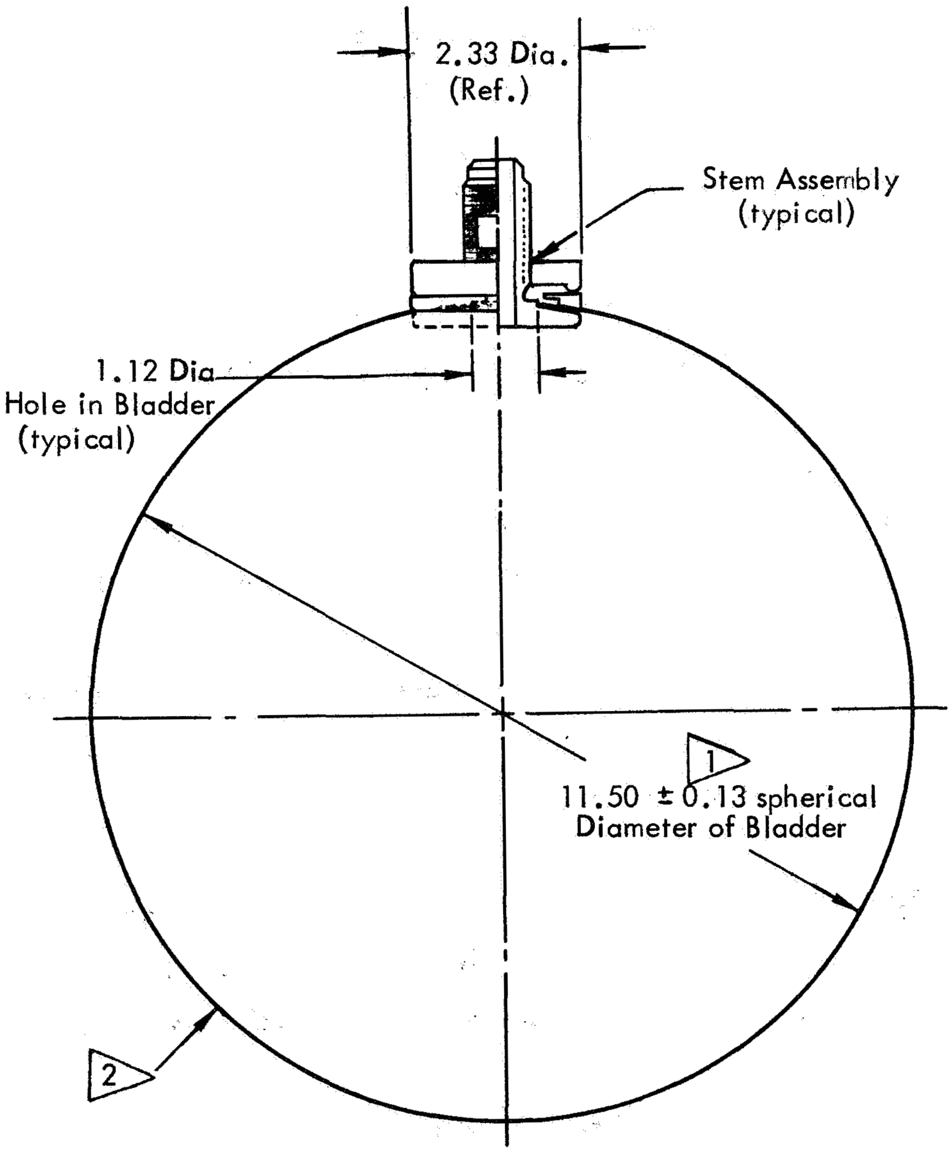
3.2 CONFIGURATION

Seven multi-ply 12-liter spherical bladders were fabricated to the dimensions shown in Figure 1. The attachment stem was supplied by NASA LeRC. Each bladder consisted of low permeability barrier plies of Mylar, Kapton or No. 3711 film and flex-life enhancing substrate plies of Nomex or MERFAB as outlined in Table 1. An extra inner barrier ply designated "O" was added to bladders 25-MM-12-1 and 50-X-10-1 to support the collapse control device.

Each ply consisted of a single layer of material, either barrier film or substrate material, and was formed of twelve equal gores. Lap seams, 0.5 inch wide, were used to join the gores and attach a 3.5 inch diameter south polar cap.

3.3 COLLAPSE CONTROL DEVICE

The design requirements for the collapse control device were (1) that it be an integral part of the bladder construction, (2) that it be rigid enough at -423°F to direct the collapse pattern of the bladder, (3) that it be tough enough at



1 When bladder pressurized to 12" H_2O

2 Multiple plies, gores, polor caps, etc. not shown

FIGURE 1 12 LITER SPHERICAL POLYMERIC EXPULSION BLADDER

TABLE 1

BLADDER CONSTRUCTION

Bladder Number [1]	Material		Number Barrier Plies [2]	Number Substrate Plies [2]
	Barrier Ply	Substrate Ply		
50-K-10-1	0.50 mil Kapton	2. mil Nomex	10; plies number 2, 3, 4,5,6,8,9,10 11 & 12	2; plies number 1 & 7
25-M-10-0	0.25 mil Mylar C	--	10.	--
25-M-10-1	0.25 mil Mylar C	--	10.	--
25-MM-12-0	0.25 mil Mylar C	0.6 mil MERFAB	12; plies number 3,5, 6,8,9,11,12,14,15, 17,18, & 20	8; plies number 1, 2,4,7,10,13,16, & 19
25-MM-12-1	0.25 mil Mylar C	0.6 mil MERFAB	13; plies number 0,3, 5,6,8,9,11,12,14,15, 17,18, & 20	8; plies number 1,2,4,7,10,13, 16 & 19
50-X-10-0	0.5 mil N o.3711 Film	2.mil Nomex	10; plies number 2,3,4, 5,6,8,9,10,11 & 12 [3]	2; plies number 1 & 7
50-X-10-1	0.5 mil No. 3711 Film	2. mil Nomex	11; plies number 0, 2,3, 4,5,6,8,9,10, 11 & 12	2; plies number 1 & 7

[1] -1 bladders contained collapse control device
[2] Plies numbered from the inside out. "O" ply added to support collapse control device.
[3] When disassembled after testing, this bladder was found to have two extra external barrier plies.

-423°F to resist shattering under the bending load applied by the bladder and (4) that it be flexible enough at room temperature to allow insertion of the bladder through the neck of the test dewar. An initial attempt to meet these requirements with polyurethane rods longitudinally reinforced with glass fibers failed when the material proved to be far too rigid at room temperature. The final design for the collapse control device consisted of three solid, half-round polyurethane rods bonded to a 5 mil Kapton header as shown in Figure 2. This in turn was bonded to the outside of the inner ply of the bladder, Figure 3. The inner ply was an essential part of the collapse control device since it had to hold the device against the walls of the test dewar until the device was rigidized by the liquid hydrogen.

It had been planned to bond the device to the inner surface of the inner ply so that the flat side of the half-round rods would face outward. This would have provided the maximum rigidity for the device at -423°F and would have caused the load on the inner ply during collapse of the bladder to be a compressive load on the bond between the device and the barrier ply. This positioning proved to be incompatible with the bladder fabrication processes and the collapse control device was bonded on the outer surface of its barrier ply.

The helium gas fill tube also controlled the collapse of the bladders to a certain extent. The tube was designed to come within 2.0 inches of the bottom of the test dewar and so limited the vertical motion of the bladders during collapse. This occurred on bladders with and without the integral collapse control device.

3.4 FABRICATION AND INSPECTION PROCEDURES

The following procedures were employed by Sea-Space Systems, Inc. for fabrication and inspection of the test bladders. All bladder fabrication and testing was conducted under clean-room conditions at a temperature of 75 ± 3°F.

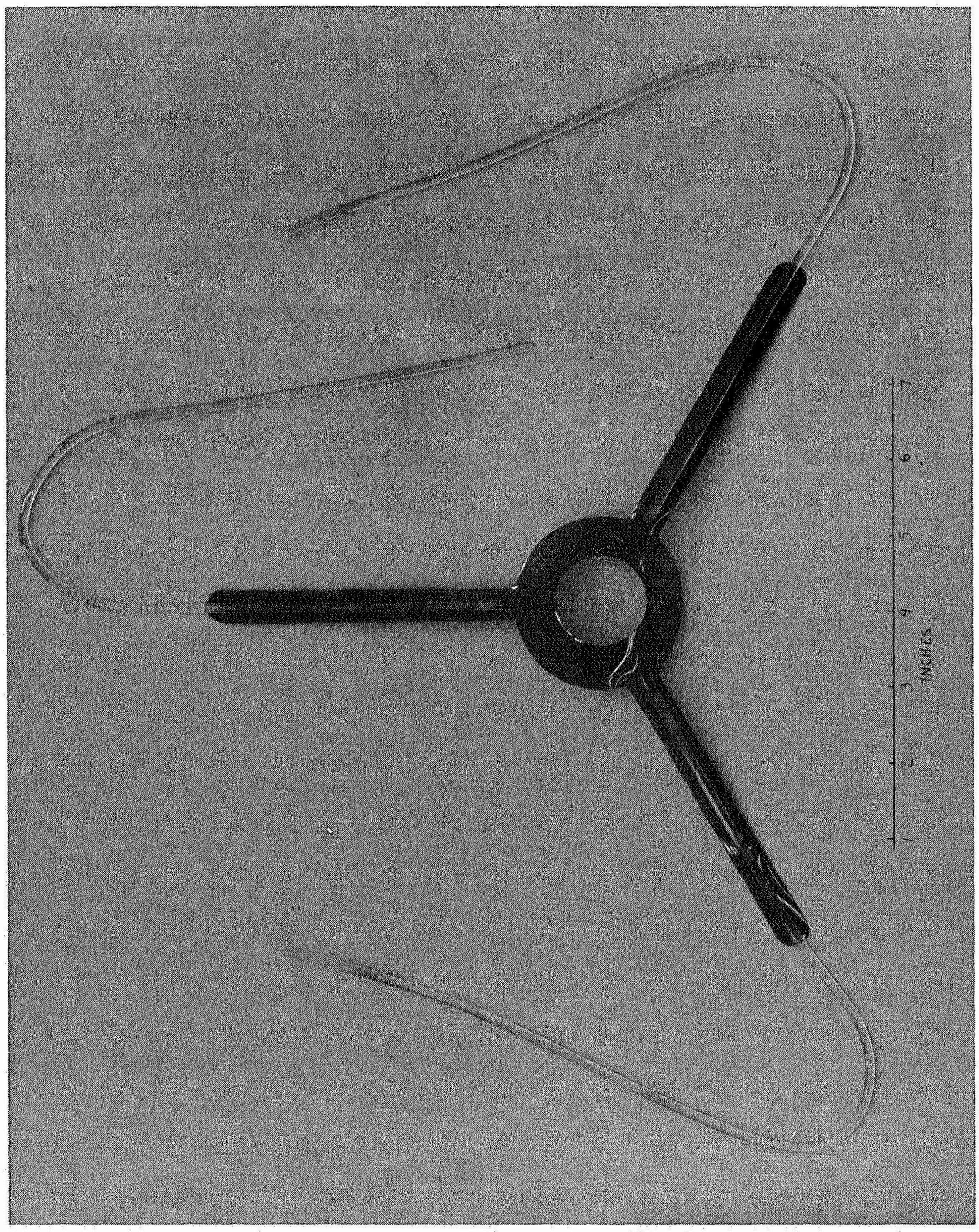


FIGURE 2 COLLAPSE CONTROL DEVICE

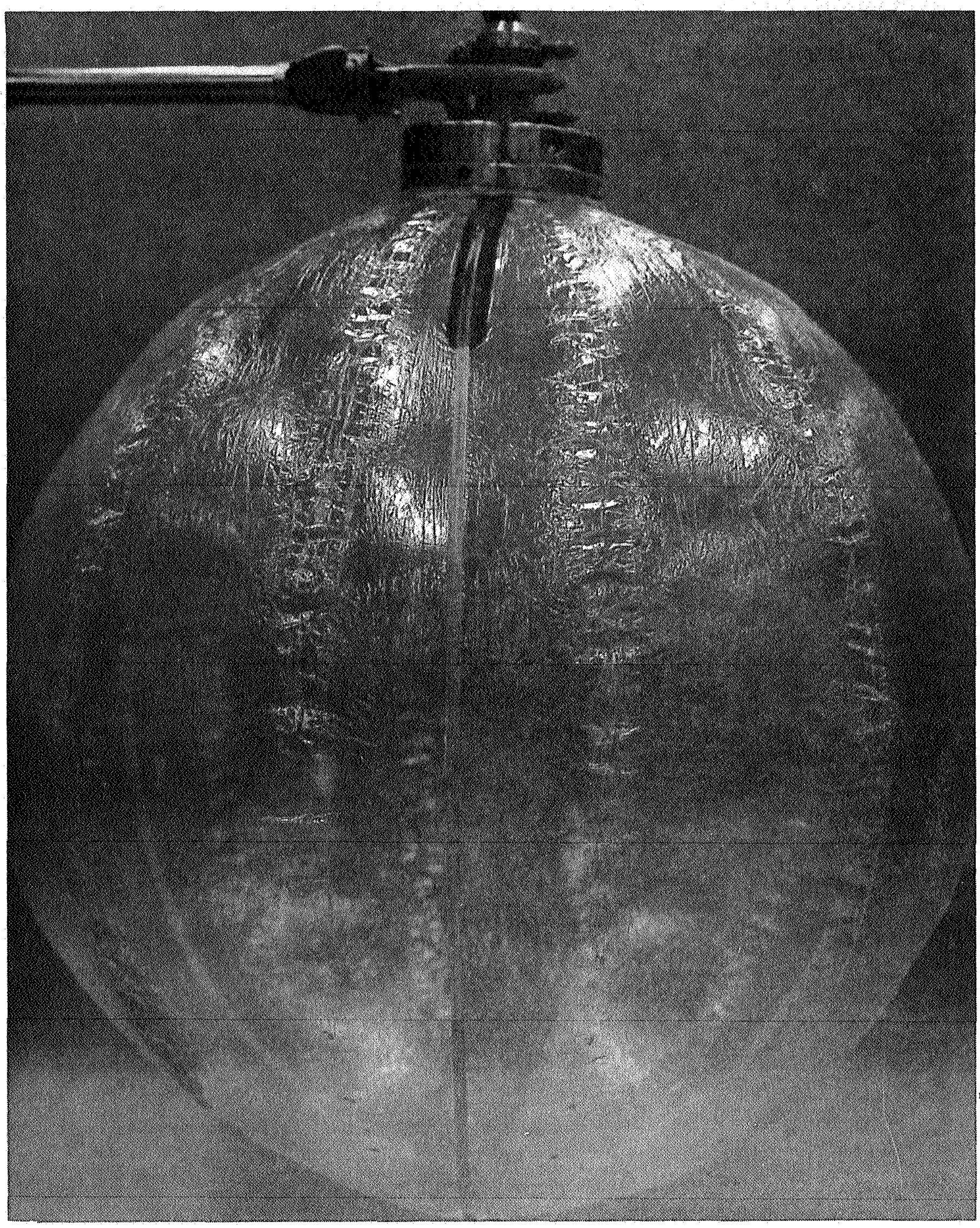


FIGURE 3 COLLAPSE CONTROL DEVICE BONDED ON INNER PLY

A. Inspection of As-Received Barrier Film

1. A panel of barrier film 18 x 92 inches was fastened in a rubber gasketed retangular frame. The panel was handled and mounted by a 1 inch border on all edges; the actual test area being 16 x 90 inches. The panel was unstressed after mounting, free of wrinkles but not stretched in the frame.

2. The frame and panel were immersed in distilled water until the panel was 4 inches beneath the surface of the water and geometrically parallel to the free surface of the water.

3. Helium was fed under the panel forming a large bubble until the strain in the film reached a maximum of 3% or until excess helium escaped at the edges. Two extensometers 60 inches apart were used to determine the strain. The test conditions were maintained for 4 hours. Make-up helium was added as required to maintain bubble dimensions.

4. The coordinates of any pinholes, as located by helium bubbles, were recorded on an inspection sheet.

5. The frame and test panel were removed from the water, dried and the pinholes marked. The data from this inspection became a part of the documentation of each bladder subsequently fabricated from the material and gores were cut only from areas which were free of pinholes.

B. Barrier Ply Fabrication

1. Gore Cutting

The previously tested sheet of barrier film was taped flat to a work table and using an aluminum template as a guide, the gores were cut out with a scalpel. After cutting each gore,but before the template was removed from the film, colored indexing dots were placed along the edges of the gore.

2. Gore Seaming

a. Each gore was solvent cleaned with MEK, clean cotton gauze and "Q" tips.

b. A half-inch wide band of S-110 adhesive was brushed on one edge of the gore to be bonded. The adhesive was modified by solvent dilution to produce a dried adhesive layer 1/2 to 1 mil in thickness.

c. A special jig was used to supply the backing surface for forming the longitudinal seams. The surface of the jig was 5/8 inch wide and comprised approximately 240 degrees of a circle 5.75 inches in radius. The drying period for the adhesive, approximately 2 minutes, was used to mount the edge of the adhesive coated gore on the jig, adhesive side up. The neighboring gore was held to one end of the jig and progressively rolled down onto the wetted margin of the lap. The index marks placed on the gores as they were cut were used to assure proper alignment. The gores were pressed firmly together so the adhesive tack would hold their location until the bond was thermally set.

d. An electrically heated sealing wheel 4 inches in diameter was rolled along the seam overlap at a rate of about 0.5 inch per minute. The wheel temperature was thermostatically controlled to within ± 2°F of the bonding temperature of the film: 160°F for Mylar and Kapton, 150°F for No. 3711 film. Sealing pressure was controlled manually by the operator to be great enough to cause adhesive flow and wetting and light enough to prevent adhesive from being extruded out of the bond area.

3. South Polar Cap Sealing

The outer 0.5 inch annulus of a 3.5 inch disk of the barrier film was coated with adhesive as in paragraph 2b. This was heat sealed to the assembled gores of the barrier ply as in paragraph 2d. except that the backing force was provided by a round, flat surface support fixture covered with 1/8-inch thick soft foam.

4. Barrier Ply Inspection

a. Visual Examination

The north polar ends of the gores were gripped and sealed between two rubber gaskets on the stem attachment assembly and the ply inflated with helium to a pressure of 5 inches of water. The ply was visually inspected for uniformity of seams, evidence of material defects and cleanliness. The diameter was measured with a pair of soft-tipped calipers. Defective seams were repaired by dismounting the ply from the stem attachment and re-heat sealing per paragraph 2 d. Minor flaws were patched per the following Section 5. Major material flaws or dimensional inaccuracy called for rejection of the ply.

b. Ply Porosity Test

The ply, mounted on the stem assembly with the two rubber gaskets, was placed in the bell-jar porosity tester shown schematically in Figure 4, purged with helium and then pressurized to an internal pressure of 16 inches of water with helium. This pressure was maintained between the bladder pressure manometer and the back pressure manometer. The rate of bubble release from the by-pass

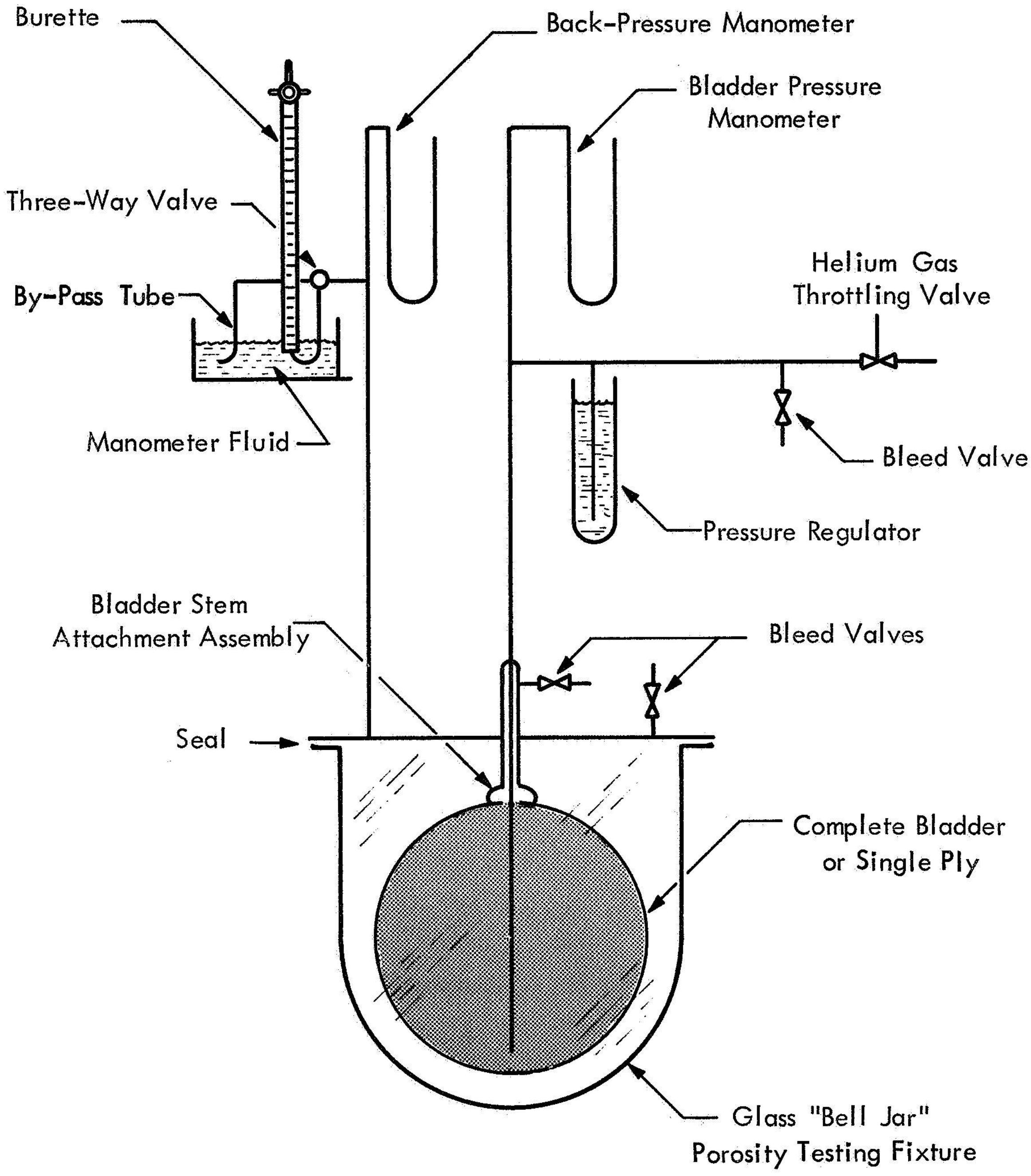


FIGURE 4 SCHEMATIC FOR BLADDER AND PLY POROSITY TESTING

dip tube was counted until an equilibrium rate was established. The three-way valve was turned to direct the bubble flow into the burette. Leakage was measured for a total of 30 minutes with the burette being read every 6 minutes to verify that an equilibrium state had been established. The maximum allowable leakage rates for the various barrier plies were 18 cc/minute for Mylar and 10 cc/minute for Kapton and No. 3711 film. Leakage rates in excess of these values called for repair or rejection of the ply as previously mentioned.

5. Patching of Barrier Plies

a. Patches 1/4 to 1/2-inch in diameter were cut from the barrier ply material. The patch size was dictated by the size of the flaw to be repaired, but in no case was greater than 1/2-inch in diameter.

b. The patch and the area of the ply containing the flaw were solvent cleaned with MEK.

c. S-110 adhesive was applied to the patch and the bladder and air dried.

d. The patch was heat sealed to the ply with a sealing iron controlled as for the gore sealing.

C. Substrate Ply Fabrication

The gore cutting, gore seaming and south polar cap sealing for the substrate plies was the same as for the barrier plies. Substrate plies of MERFAB were bonded with S-110 adhesive. Bostik 4034 adhesive was used for Nomex plies.

D. Final Assembly of the Bladder

The final assembly of the bladder plies in the stem attachment was as shown in Figure 5. A collar of barrier film material was bonded to the stem and sucessive

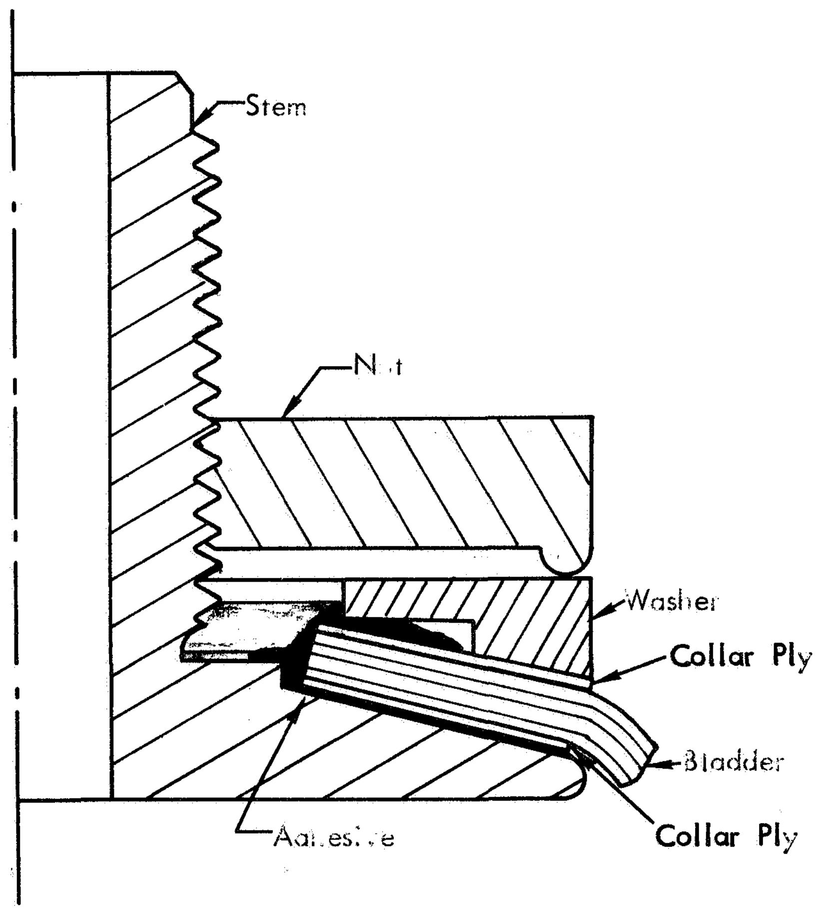


FIGURE 5 STEM ASSEMBLY CROSSECTION

plies of the bladder and a second collar were added using the bonding techniques for gore seaming. The ends of the gore seams, which had been left unbonded to facilitate ply testing and allow slipping the exterior plies onto the bladder assembly, were bonded at this time. Each ply was rotated 15° in azimuth as it was added to the bladder to stagger the gore seams.

A continuous heavy coating of adhesive was applied over the ends of the gores in the stem attachment. On bladder 50-K-10-1, this coating was formed by the squeeze-out of the S-110 and Bostik 4034 adhesives used for gore bonding and adequately sealed the bladder. On subsequent bladders these adhesives did not provide a leak-proof seal and epoxy/polyamide adhesive was added.

E. Bladder Inspection

1. Visual Inspection and Dimensioning

The assembled bladder was pressurized to 12 inches of water with helium. The bladder was visually inspected for perfection of nesting, absence of inter-ply folds or wrinkles, and cleanliness of the assembly. The equatorial and polar diameters were measured with soft-tipped calipers.

2. Bladder Porosity Test

The procedure and equipment, Figure 4, used for the ply leakage test was used for testing the porosity of the assembled bladder except that the internal helium pressure was raised to 28 inches of water. The bladder was pressurized for 24 hours to establish equilibrium conditions and then the back-pressure was vented under the burette for 30 minutes. A value of zero leakage during the 30 minute test period was the acceptance criteria.

3. Receiving Inspection Test - Boeing

Upon receival by The Boeing Company, the bladder was again dimensionally inspected and leak tested as in paragraph E 1 and E 2. Both Sea-Space Systems, Inc. and The Boeing Company found it convenient to add a hydrostatic bubble column to the leak test apparatus to control the bladder pressure during the 24 hour stabilization period. Figure 6 shows The Boeing Company apparatus.

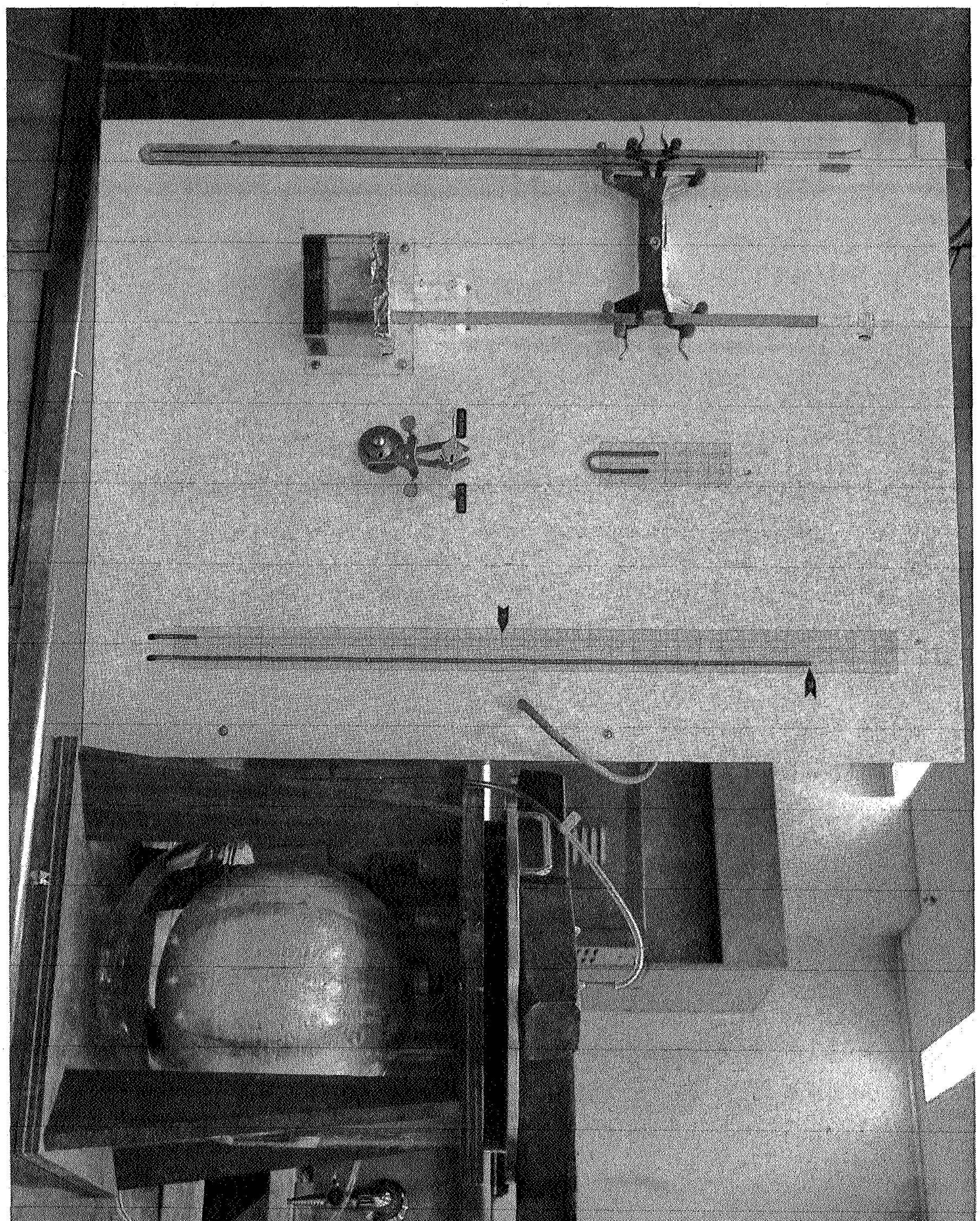


FIGURE 6 RECEIVING INSPECTION POROSITY TEST FIXTURE

4.0 TASK II - BLADDER TESTS

4.1 TEST OBJECTIVES

These tests were designed to experimentally determine the following:

a. The porosity of the test bladders at -423°F to helium gas at -423°F.

b. The effect of a 24 hour soak period on a liquid hydrogen expulsion bladder in the half-expelled condition and the amount of hydrogen gas which diffuses into the expelling helium gas.

c. The cyclic endurance limit of the test bladders when expelling liquid hydrogen through the outward expulsion mode, with a goal of twenty-five cycles.

d. The expulsion efficiency, for water at room temperature, of any bladders which complete twenty-five expulsions of liquid hydrogen.

4.2 TEST BLADDERS

The bladders fabricated under Task I, as defined in Table 1, were used as the test specimens. The porosity to room temperature and -423°F helium gas was measured for all seven bladders. One bladder of each type barrier ply material was exposed to the 24 hour hydrogen diffusion soak. Bladders 50-K-10-1, 25-MM-12-1, 25-M-10-0 and 50-X-10-0 were selected for this test.

The cyclic expulsion capabilities of all seven bladders was determined and the expulsion efficiency was measured with water for bladders 50-X-10-0 and 50-X-10-1

4.3 TEST EQUIPMENT

A. Facilities

All bladder tests with liquid hydrogen were conducted on Test Pad 3 in Area 41 of the Boeing Tulalip Test Site. Figure 7 presents an aerial view of Area 41, while Figure 8 shows Pad 3 with the test apparatus installed. Details of the controlling and

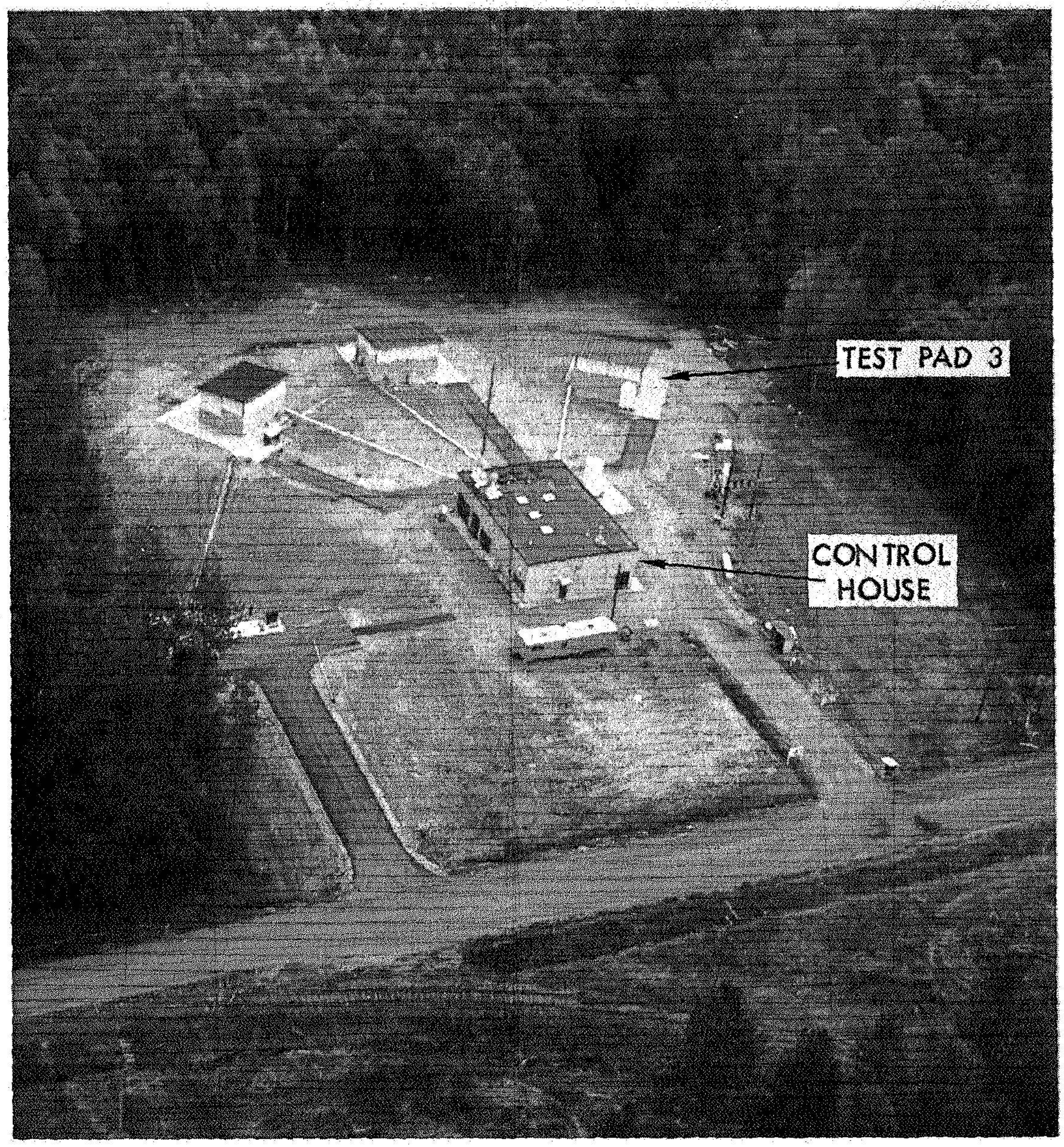


FIGURE 7 AREA 41 - TULALIP TEST SITE

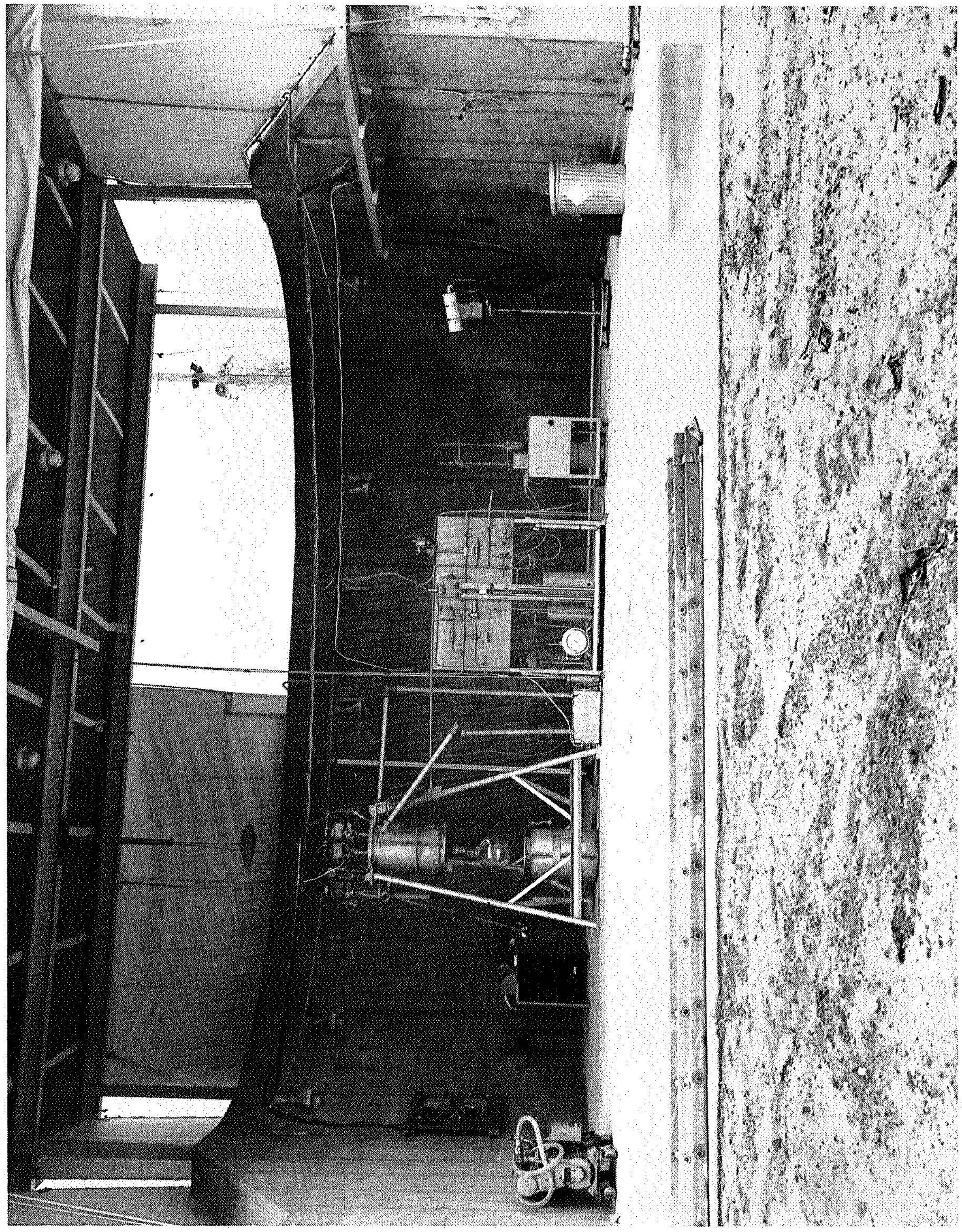


FIGURE 8 PAD 3 WITH TEST APPARATUS INSTALLED

data recording equipment are shown in Figure 9.

B. Apparatus

The configuration of the test apparatus was as shown in Figure 10 and consisted of the following major items.

1. The Test Dewar was an unsilvered vacuum insulated 12-liter spherical flask manufactured by H. O. Martin Company of Evanston, Illinois. Attachment and sealing was accomplished through a 3-inch glass pipe flange. Figure 11 shows the test dewar, attachment hardware, helium gas fill tube and collander chains.

2. The Upper Cryostat was a vacuum-insulated stainless steel dewar fabricated by The Boeing Company. The bottom was designed to mate with and act as a closure for the lower cryostat. The upper cryostat was used to condition the liquid hydrogen and helium gas before admitting them into the test dewar.

3. The Lower Cryostat was a vacuum-insulated stainless steel dewar fabricated by The Boeing Company. It contained the liquid hydrogen for immersion of the test dewar during the -423°F helium porosity tests and the diffusion tests. Figure 12 shows the upper and lower cryostats in the closed position. For the cycling tests the lower cryostat was lowered, Figure 13, to permit photographic coverage.

4. The Helium Pressurization Heat Exchanger was located in the ullage volume of the upper cryostat. It was used to cool the gaseous helium to -423°F for porosity measurements and expulsion cycling.

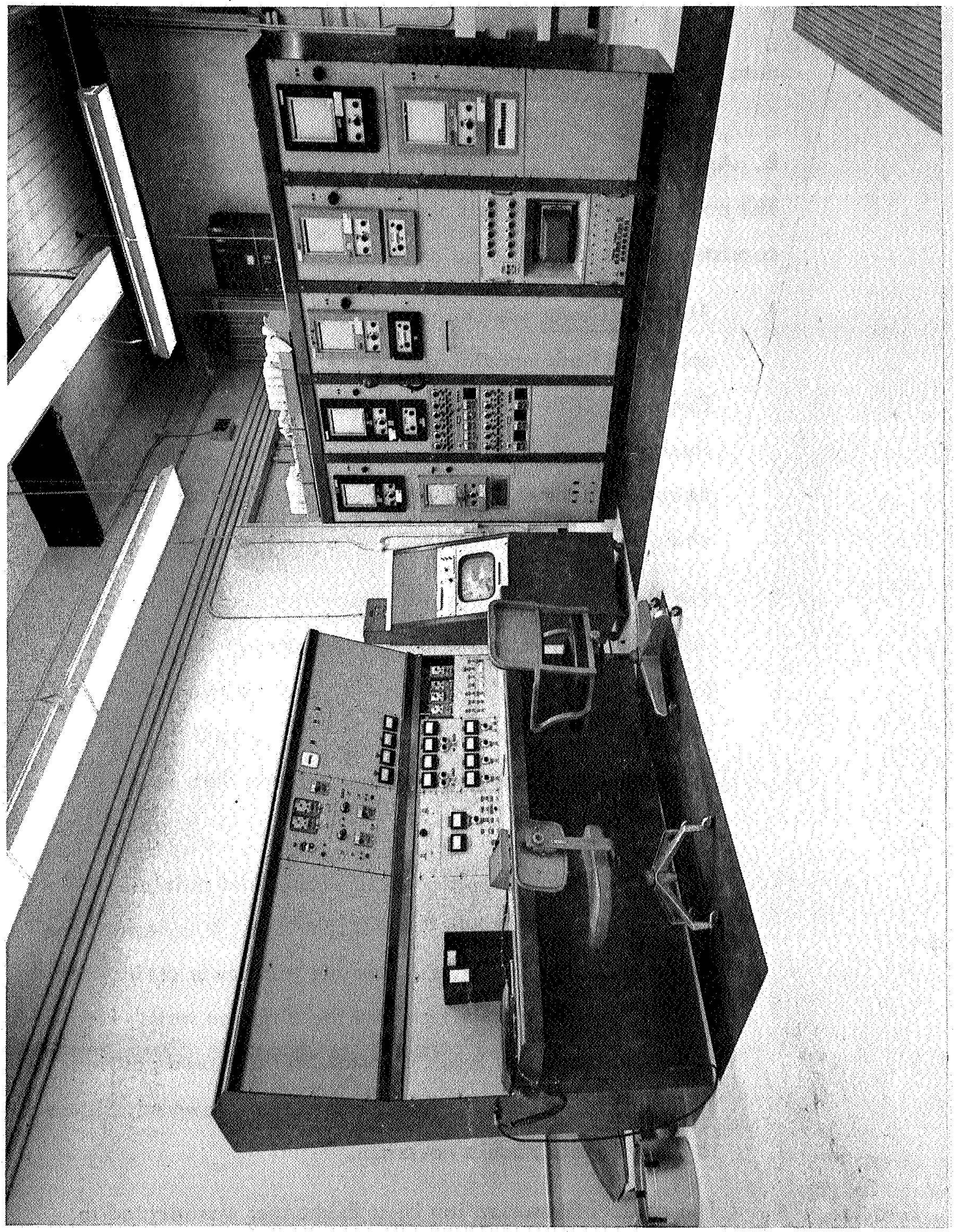


FIGURE 9 CONTROLLING AND DATA RECORDING EQUIPMENT

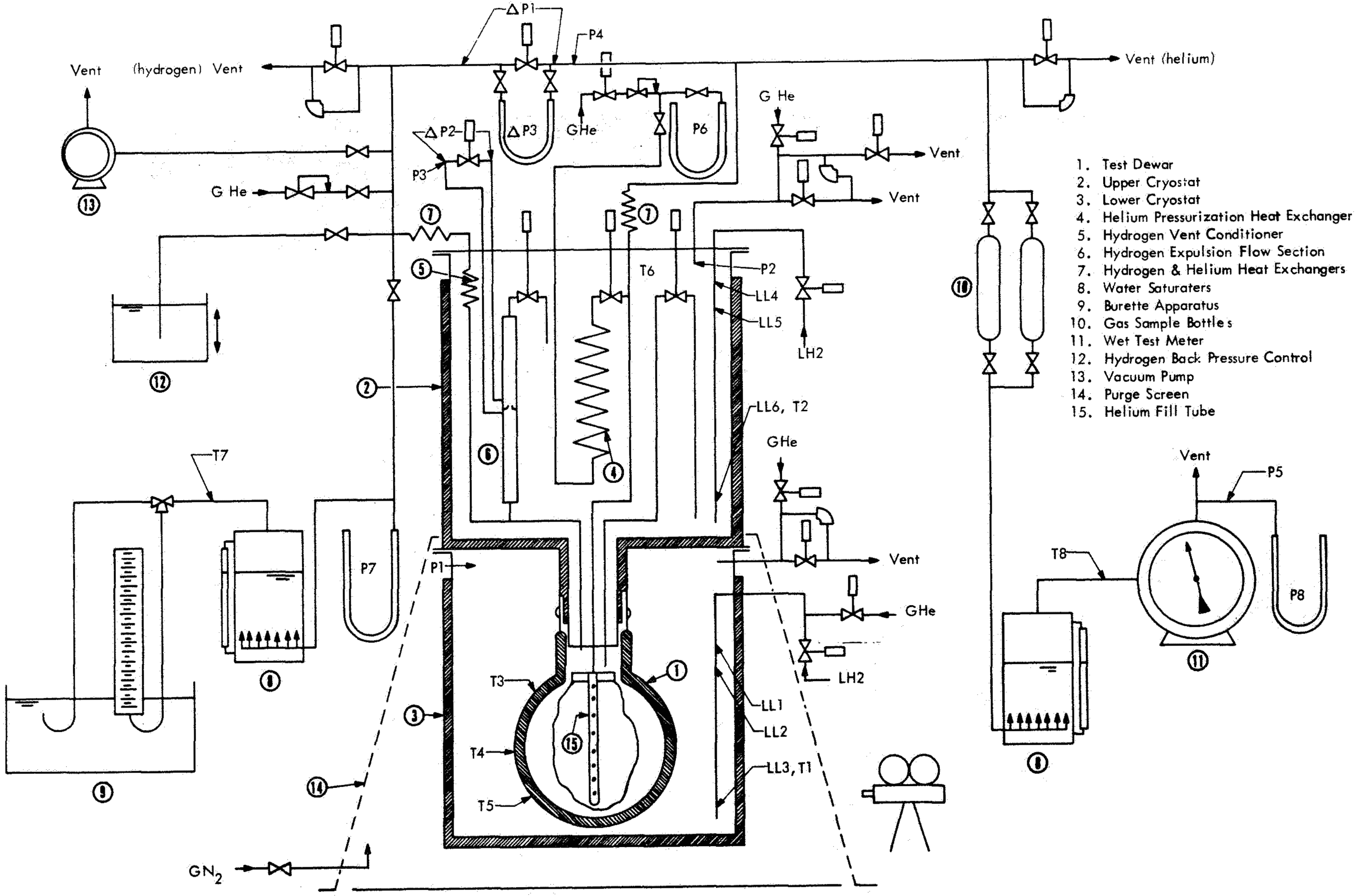


FIGURE 10 TEST SYSTEM SCHEMATIC

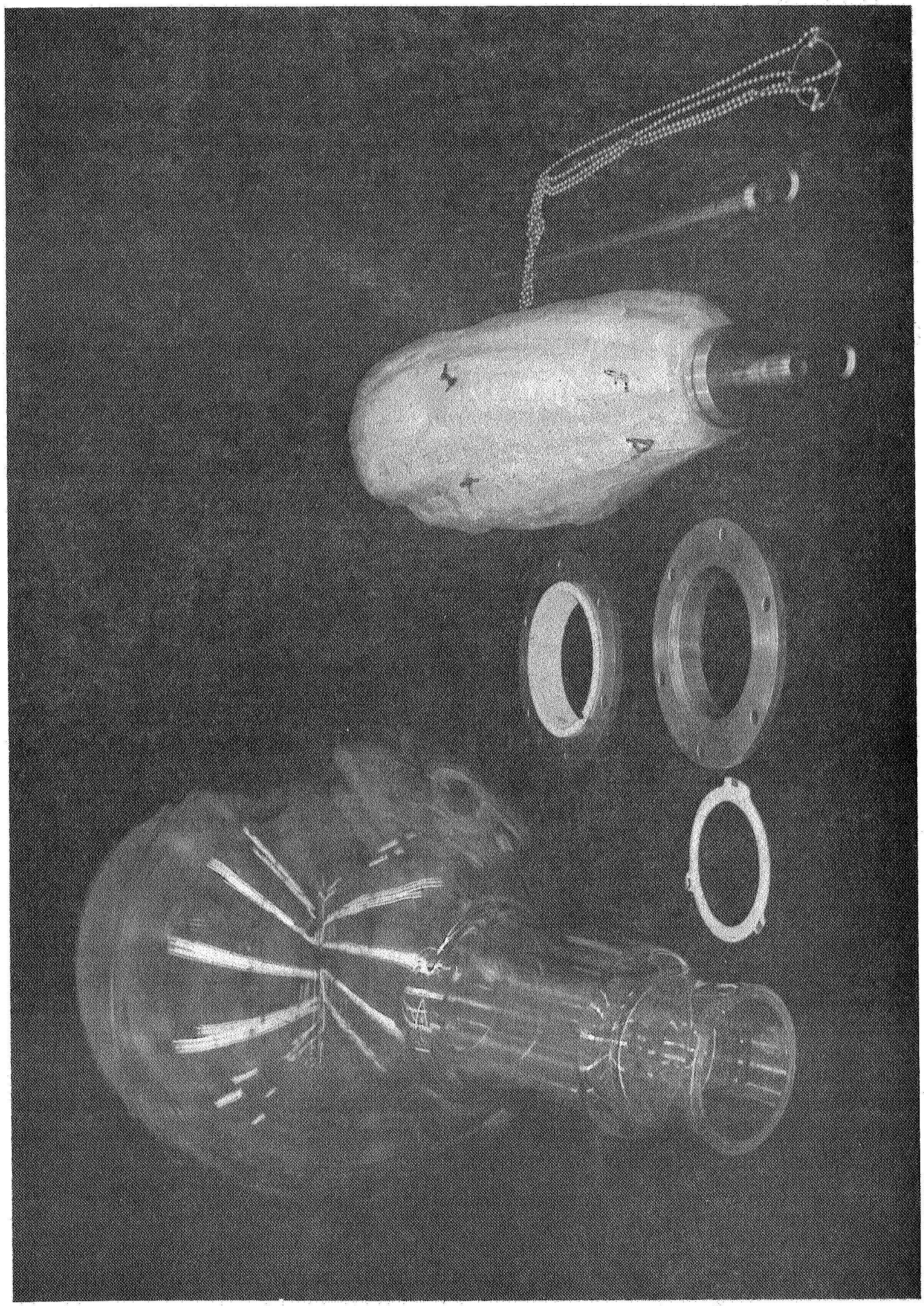


FIGURE 11 BLADDER, DEWAR AND RELATED HARDWARE

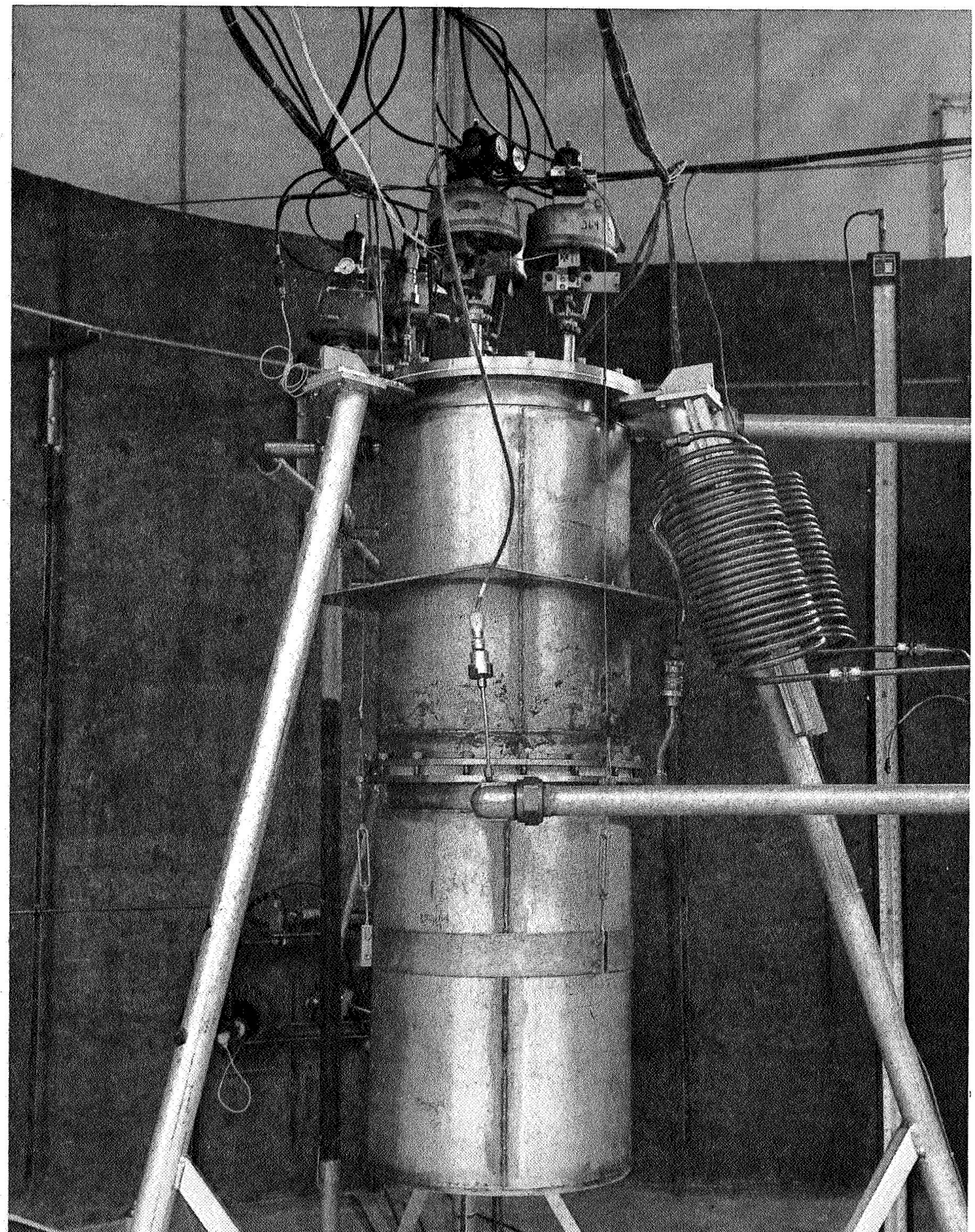


FIGURE 12 CRYOSTATS IN CLOSED POSITION

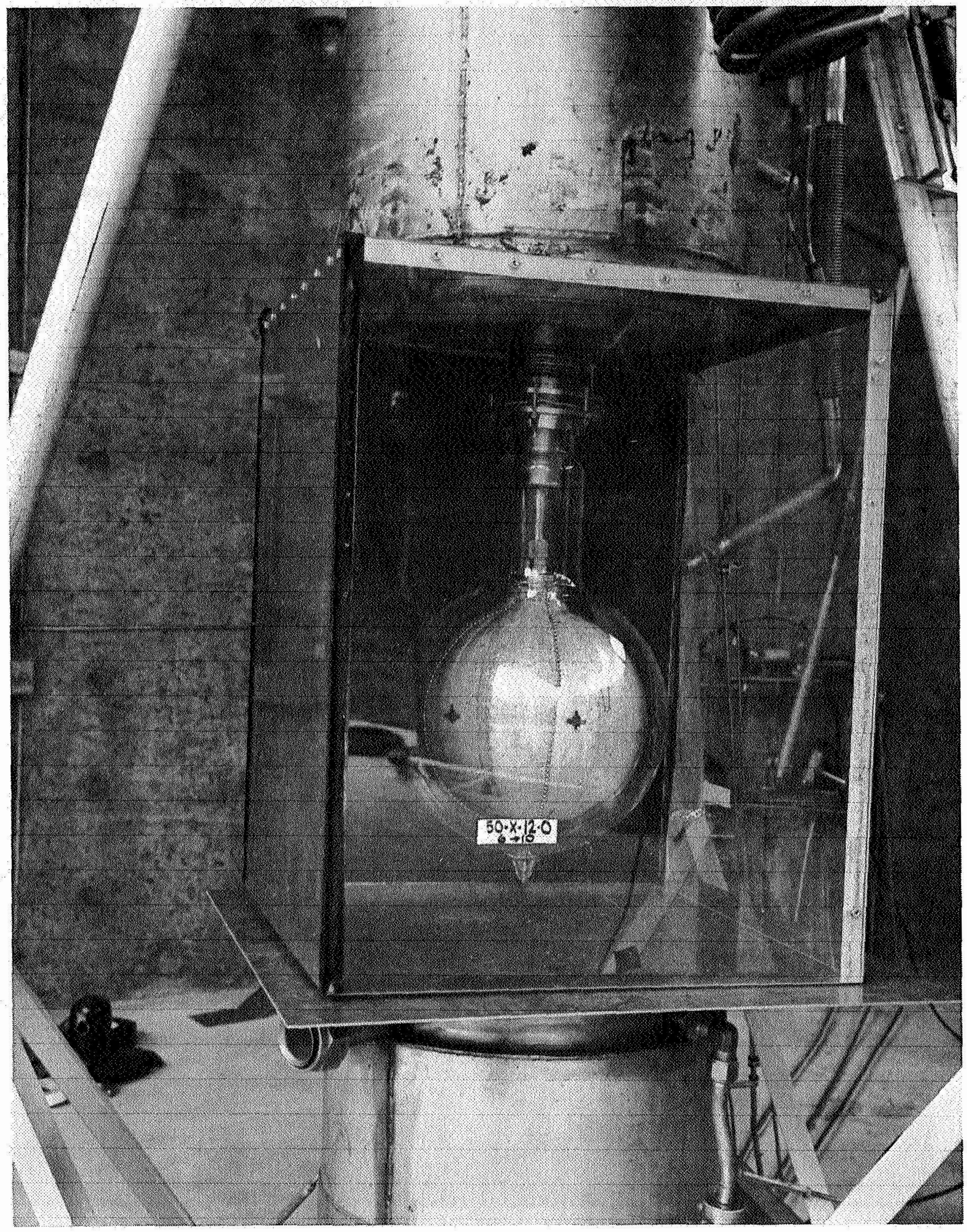


FIGURE 13 OPEN CRYOSTATS WITH PURGE SCREEN

5. The Hydrogen Vent Conditioner was located in the ullage volume of the upper cryostat. Its purpose was to prevent liquid hydrogen from reaching the warm vent lines and producing uncontrolled pressure surges in the test dewar.

6. The Hydrogen Expulsion Flow Section was located in the upper cryostat. It was used to measure and control the liquid hydrogen expulsion from the bladder at 1 gpm. The section was completely submerged in the upper cryostat to obtain single phase flow for greater accuracy in the flow measurements.

7. The Hydrogen and Helium Heat Exchangers were located external to the cryostats and were used to increase the temperature of the vented gases from the test dewar to ambient. These are the two coils to the right in Figure 12.

8. The Water Saturaters were used to saturate the evolved gases from the test dewar to insure accurate determination of the gas volumes.

9. The Burette Apparatus (Figure 14) was used to measure the porosity or leakage of the test bladders.

10. The Gas Sample Bottles were used to trap a portion of the gas from the helium side of the bladder during the diffusion test. The samples were then analyzed to determine the quantity of hydrogen in the helium.

11. The Wet Test Meter was used to measure the quantity of gas evolved from the helium side of the bladder during the diffusion test.

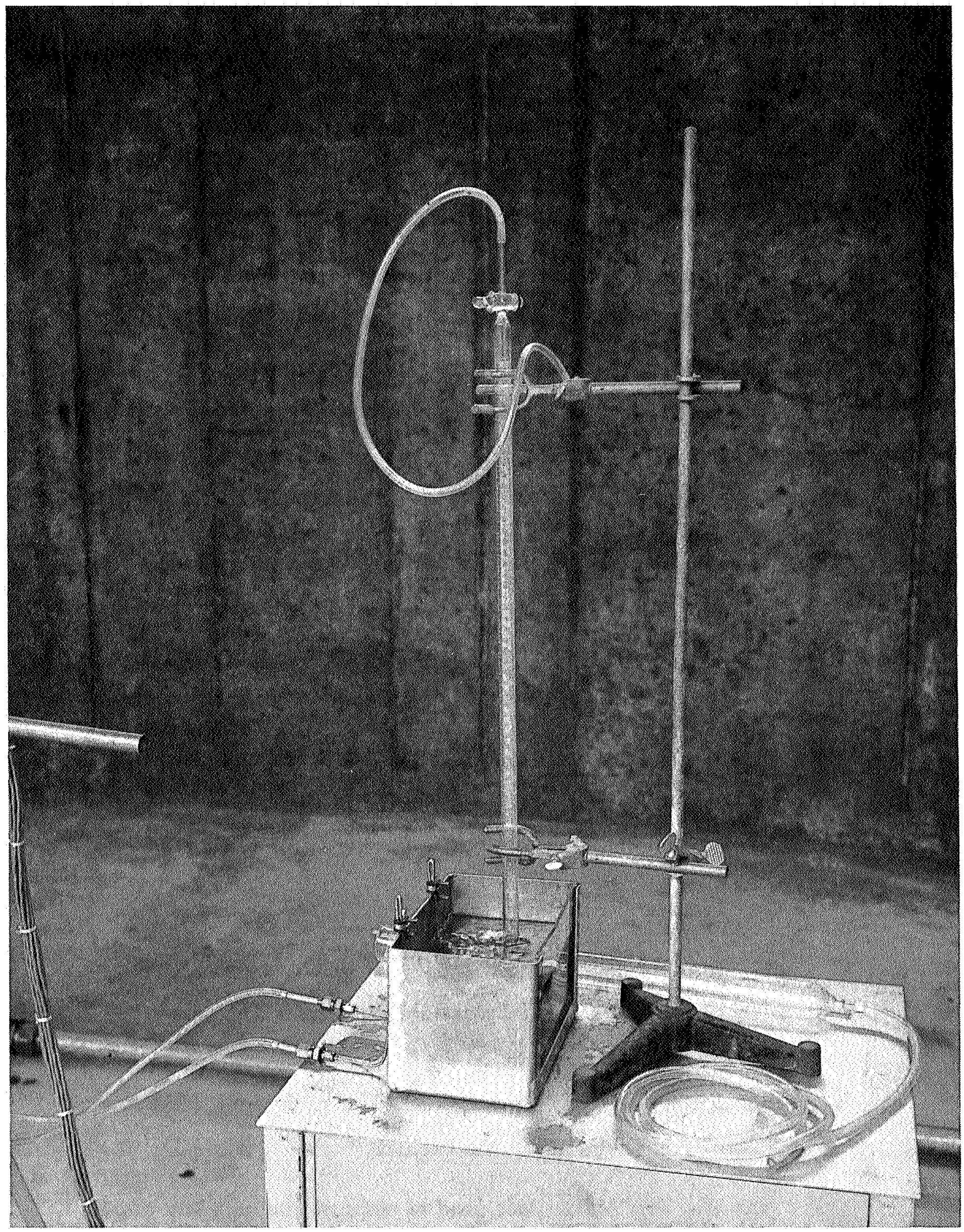


FIGURE 14 BURETTE APPARATUS

12. The Hydrogen Back Pressure Control was used to maintain zero pressure differential across the bladder during the diffusion test.

13. The Vacuum Pump was used to vacuum purge the test dewar and portions of the test system prior to starting the tests.

14. The Purge Screen, a hinged acrylic sheet box, was used to maintain a dry nitrogen atmosphere around the test dewar during the expulsion test runs. Without the screen, frost formation on the test dewar would have prevented the required photographic coverage of the expulsion cycles while the test dewar was exposed to ambient temperature air.

C. Instrumentation

Pressures were sensed by standard strain gage transducers or water manometers. Test temperatures were sensed by copper-constantan or chromel-constantan thermocouples. Liquid level and control detectors used carbon resistors as sensors. Outputs were recorded on Leeds and Northrup Speedomax H Strip-Chart recorders. Signal conditioning equipment was built by The Boeing Company. All equipment used was calibrated and certified through Boeing's standard Cal-Cert procedures. The instrumentation points shown on Figure 10 are detailed in Table 2.

Two 16mm cameras were placed around the test dewar at approximately 90° to each other during the expulsion tests to give as near complete coverage of the bladders as possible. A closed circuit television system, visible in Figure 9, provided the test engineer with visual monitoring of the tests. The television system permitted the test engineer to activate the cameras during significant events and leave them off during some of the time consuming fills and expulsions.

TABLE 2
INSTRUMENTATION LIST
LH_2 POSITIVE EXPULSION BLADDER TEST

Parameter	Description	Range	Accuracy	Record/Display	Recorder
P1	Lower Cryostat Pressure	0-10 psig	±2%	Panel meter	-
P2	Upper Cryostat Pressure	0-10 psig	±2%	Panel meter	-
P3	Test Dewar Flow Section Inlet Pressure	0-5 psig	±2%	Stripchart/P.M.*	"A"
P4	Bladder Pressure	0-5 psig	±2%	Stripchart/P.M.	"B"
P5	Wet Test Meter Pressure	0-2 psig	±2%	Stripchart/P.M.	"C"
P6	Helium Inlet Manometer	60 in H_2O	-		-
P7	Test Dewar Outlet Manometer	30 in H_2O	-		-
P8	Wet Test Meter Outlet Manometer	8 in H_2O	-		-
ΔP1	Test Dewar - Bladder Differential Pressure	0-2 psid	±2%	Stripchart	"D"
ΔP2	Test Dewar - Outlet Flow Differential Pres.	0-2 psid	±2%	Stripchart	"E"
ΔP3	Test Dewar - Bladder Manometer	0-30 in-H_2O	-		-
T1	Lower Cryostat Stillwell Temperature	30-560°R	±10°	Stripchart	"F"
T2	Upper Cryostat Stillwell Temperature	30-560°R	±10°	Stripchart	"F"
T3	Test Dewar Shell Temperature	300-560°R	±5°	Stripchart	"G"
T4	Test Dewar Shell Temperature	300-560°R	±5°	Stripchart	"G"
T5	Test Dewar Shell Temperature	300-560°R	±5°	Stripchart	"G"
T6	Bladder Helium Inlet Temperature	30-560°R	±10°	Stripchart	"F"
T7	Burette Inlet Temperature	460-560°R	±3°	Stripchart	"G"
T8	Wet Test Meter Gas Temperature	460-560°R	±3°	Stripchart	"G"
LL1	Lower Cryostat Upper Liquid Level	LH_2	-	Light	
LL2	Lower Cryostat Middle Liquid Level	LH_2	-	Light	
LL3	Lower Cryostat Lower Liquid Level	LH_2	-	Light	
LL4	Upper Cryostat Upper Liquid Level	LH_2	-	Light	
LL5	Upper Cryostat Middle Liquid Level	LH_2	-	Light	
LL6	Upper Cryostat Lower Liquid Level	LH_2	-	Light	
LL7	Test Dewar Vent Liquid Sensor	LH_2	-	Light	

*P.M. = Panel Meter

4.4 TEST DESCRIPTIONS

A. Porosity Test

The helium permeation and leakage through the bladders was measured as an indication of bladder quality. Porosity tests at 75°F and -423°F were run on each bladder at the initiation of testing and a -423°F test was made after every fifth expulsion cycle. At the completion of testing, a final helium porosity test was made at 75°F.

B. Diffusion Test

Immediately following the initial porosity test, and while the test dewar was still immersed in liquid hydrogen, the test dewar was filled with liquid hydrogen. One-half of the liquid hydrogen was expelled and the system was adjusted so there was zero differential pressure across the bladder. After 24 hours in this condition the remaining liquid hydrogen in the test dewar was allowed to evaporate and the gas from the helium side of the bladder was analyzed.

C. Cyclic Expulsion Test

Following either the initial helium porosity test or the diffusion test, the exterior of the test dewar was surrounded with ambient temperature dry nitrogen gas. The test dewar was alternately filled with liquid hydrogen and emptied by outward expulsion with the bladder. The sequence was repeated until the bladder failed or until 25 cycles had been completed.

D. Expulsion Efficiency Test

As a measure of the remaining integrity of the bladder following the cyclic expulsion tests, the expulsion efficiency of two bladders was determined with water at ambient temperature.

4.5 TEST PROCEDURES

The procedures used to accomplish the liquid hydrogen testing were divided into the following six groups:

A. The Vacuum Purge was performed on the test dewar, upper cryostat, and portions of the test system prior to the initial filling of the system with LH_2. The vacuum purge was used to clear the system of atmospheric gases and to overcome the difficulties inherent in helium flow purge. The vacuum purge was performed twice, each time the system was back-filled with gaseous helium. Precautions were included in the detailed procedures to prevent excessive differential pressure across the bladder.

B. The Cryostat Filling, both upper and lower, was accomplished by transfer from an 800 gallon dewar. Preparatory to filling the lower cryostat a flow purge was made with gaseous helium to remove condensibles. When filling the lower cryostat the pressure was maintained below 5 psig to prevent collapsing the test dewar. Both cryostats were equipped with automatic liquid level controls.

C. The Porosity Measurements were accomplished with both cryostats full of liquid hydrogen. The bladder was pressurized to a constant 28 inches of water with -423°F helium during the equilibrium soak and measurement periods. The burette apparatus, Figure 14, with a maximum back-pressure of 3/4 inch of water, was used to measure the leakage of helium gas which was corrected to standard temperature and pressure.

D. The Diffusion Measurement was performed immediately following the initial porosity measurement. The test dewar was filled by slightly pressurizing the upper cryostat and allowing flow of liquid hydrogen into the dewar. One-half of the liquid hydrogen was expelled from the test dewar by pressurizing the bladder with helium. Since the lower cryostat was in the raised position prohibiting visual observation of the expulsion, the amount of liquid hydrogen expelled was measured through the flow section. At the end of the 24 hour soak period, the LH_2 in the lower cryostat was removed, and the cryostat was purged and lowered away from the test dewar. The remaining LH_2 in the test dewar was allowed to evaporate. The gas from the helium side of the bladder passed out through the gas sample bottles and wet test meter. The composition of the gas trapped in the gas sample bottle was analyzed on a Bendix Model 17, mass spectrophotometer.

E. Expulsion Cycling was accomplished by remote control from the block house. The fill of the test dewar was accomplished, as in paragraph D., by pressurizing the upper cryostat and allowing flow of liquid hydrogen into the test dewar. The expulsion rate was controlled to 1 gpm by the flow section outlet valve. The helium pressure was controlled to limit the pressure inside the bladder to a maximum of 1 psid during the expulsion phase. The detailed operational procedures were set up to reduce the possibility of over pressurization of the bladder as much as possible. The significant events of each fill and expulsion cycle were recorded on film by the test engineer monitoring the tests on the television system.

F. The Cryostat Emptying and Purging were relatively straightforward operations. The liquid hydrogen was either returned to the supply dewar or vented to the atmosphere. In either case, precautions were taken to prevent excessive pressure in the lower cryostat which might cause collapse of the test dewar. Verification of the purging efficiency was made during the system check-out to ensure adequate hydrogen dilution.

4.6 POST-TEST EVALUATION PROCEDURES

The recorded test data provided the basis for a comparison of the seven test bladders in regard to helium porosity, hydrogen diffusion, cyclic endurance limit and expulsion efficiency (two bladders). The following two additional techniques were used in the final evaluation of the bladder.

A. Cinematic Evaluation

A critical review of the fill and expulsion cycles of each bladder was made to qualitatively determine the fill efficiency, degree of ply separation, collapse patterns, expulsion modes and expulsion efficiency.

B. Bladder Dissection

After the final helium porosity test, five of the seven bladders were completely disassembled to determine the degree and type of failure of the individual plies and to ascertain if there was any pattern to the failures. Each ply was cut along a baseline meridian and removed from the bladder. The twelve gores, numbered consecutively from one edge of the cut, were individually examined and all tears, punctures or seam failures recorded so that failures in one ply could be coordinated with failures in all other plies.

Since the barrier plies were essentially transparent and the detection of small holes very difficult with standard visual examination, a special inspection technique was developed. The ply under inspection was placed between two crossed polarizing plastic plates and back-lighted with a fluorescent tube lightbox. The birefringence characteristics and the refractive indices of the barrier ply films produced sufficient rotation and diffusion of the polarized light to show the barrier films as a light background. Light which passed through holes or tears was not rotated and showed up as black areas. For quick viewing, the technique worked well with a single polarizing plastic plate and polarized sunglasses worn by the inspector.

5.0 TEST RESULTS

5.1 POROSITY AND EXPULSION TESTS

The results of the helium porosity, hydrogen diffusion, and cyclic endurance tests are summarized in Table 3. Specific results and evaluations for each bladder, as described in Table 1, were as follows:

Bladder 50-K-10-1

This bladder passed the receiving inspection helium porosity test at 75°F with zero leakage. It was moderately stiff, but was installed in the test dewar with no great difficulties.

Moderate ply separation and expansion of the bladder occurred during the vacuum purge of the test dewar and upper cryostat. This was subsequently found to occur to some extent on all the test bladders.

The first helium porosity test at -423°F indicated a leakage rate of 15.3 cc/min after one hour under pressure. The system was warmed and a porosity test made at ambient temperatures in the test dewar. The porosity at approximately 65°F was 0.cc/min. The test dewar was again immersed in liquid hydrogen and 1 psid established across the bladder. The porosity readings stabilized at a rate of 6.85 cc/min approximately 2 hours after the initiation of the test condition.

Cyclic Expulsion

Cycles 1 - 5

The initial fill of the warm test dewar took 18 minutes and was accomplished with no difficulties. The bladder collapse was fairly complete, but no indication of the collapse control device could be seen. The No. 1 expulsion was accomplished in accordance with the test plan.

TABLE 3

TEST DATA SUMMARY

Bladder	He Porosity, cc/min								Diffusion Test % H_2/He
	75 °F Pre-Test	-423 °F						75 °F Post-Test	
		Initial	5 Cycles	10 Cycles	15 Cycles	20 Cycles	25 Cycles		
50-K-10-1	0	6.85	1					0.11	--
50-K-10-1	0.11	11.7	2					37.	27/67
25-M-10-0	0	13.3	42.0	> 4500				960.	50/50
25-M-10-1	0	9.5	168.7	171.	185.2	185.6	412.8	52.	--
25-MM-12-0	0	0 4							--
25-MM-12-1	0.46	29.53	355.	> 4320				133.	3
50-X-10-0	1.3	37.1	56.2	> 570				640.	30/70
50-X-10-1	3.8	163.7	191.3	136	182.2	168.6	187.6	15.6	--

1 Failed to expel on 3rd cycle.

2 Diffusion Test was made after above cycles.

3 Sample contaminated when test valve failed.

4 Failed to expel on 1st cycle.

The bladder was cycled twice, but ply separation prevented filling on Cycle No. 3. A study of the photographic record of the test revealed that bladder collapse decreased and ply inflation increased with each cycle.

Considerable difficulty was experienced in removing the bladder from the test dewar after the system was warm because the gas trapped between the plies expanded the outer plies of the bladder against the walls of the test dewar.

A second 75°F helium porosity test made on the bladder in the bell jar apparatus indicated a leak rate of 0.11 cc/min. The bladder was reinstalled in the test dewar and a -423°F helium porosity test was made. After a stabilization period of 15 hours and 55 minutes the leakage rate was 11.7 cc/min. Next, the hydrogen diffusion test was conducted. The gas analysis from the diffusion test was 67% He, 27% H_2, and 5.6% N_2. The nitrogen resulted from a failure to evacuate the gas feed line on the mass spectrophotometer.

An attempt to rerun the cyclic expulsion tests after the hydrogen diffusion test was unsuccessful because interply inflation prevented filling the test dewar with liquid hydrogen. Pressure differentials as high as 5 psid were applied in an effort to collapse the bladder. Liquid hydrogen in the neck of the test dewar would move downward in small areas when the pressure was applied, but would be immediately expelled on release of the pressure.

The bladder was not dissected since the only detectable ply damage was a tear in the outer ply which occurred removing the greatly expanded bladder from the test dewar. The final 75°F helium porosity rate on this bladder was 37 cc/min.

Bladder 25-M-10-0

This bladder had a 75°F helium porosity rate of 1.23 cc/min when received from Sea-Space Systems, Inc. After an attempted repair by The Boeing Company and two attempts by Sea-Space Systems, Inc., an entirely new bladder was made. The second bladder leaked helium at a rate of 9.87 cc/min when received by Boeing, but was subsequently brought to a zero leakage condition by adding unsintered Teflon film washers and polyurethane adhesive in the attachment stem area.

The initial -423°F helium porosity rate was 13.3 cc/min. The test dewar and bladder were submerged in liquid hydrogen for over 9 hours before stabilization occurred.

The hydrogen diffusion test resulted in an internal gas composition of 50% He and 50% H_2. Liquid hydrogen was visible between the outermost plies when the cryostat was lowered at the end of the test.

Cyclic Expulsion

Cycles 1 — 5

Bladder collapse and expulsion were good for Cycle No. 1. The bladder did not collapse immediately on filling for Cycle No. 2. There appeared to be hydrogen gas between the plies and collapse occurred when this gas condensed as filling progressed. The bladder tended to collapse from the bottom up and deform around the helium feed tube. The outer ply appeared loose near the stem area during Cycle No. 3. After approximately 30 seconds of expulsion on Cycle No. 5, the outer ply was visible against the wall of the test dewar. After Cycle No. 5 the -423°F helium porosity rate was 42.0 cc/min.

Cycles 6 — 10

The bladder operation became progressively worse with each cycle. The filling was slower and less complete, probably due to entrapped hydrogen gas, and there was more liquid hydrogen between the plies. The helium leakage at -423°F was too great to maintain the 1 psig across the bladder required for a porosity test. At ambient temperature, the porosity rate was in excess of 4500 cc/min when tested in the dewar. A test at 75°F in the bell-jar apparatus yielded a helium porosity rate of 960 cc/min.

Dissection of the bladder revealed tears in all plies. The inner ply, No. 1, had a single horizontal tear at the equator of the bladder which extended half way across one gore. The next eight plies had tears in identical locations about 1 inch below the attachment stem, and in matching gores. The lengths of the tears varied, but in most plies extended all the way across the gore. Ply No. 10 was completely loose except for one gore; the tear was approximately 1.5 inches below the attachment stem. A vertical tear, 6 inches in length, extended down from the horizontal tear in one gore.

Bladder 25-M-10-1

The initial receiving inspection test on this bladder showed a helium leak rate of 1.19 cc/min, and the bladder was returned to Sea-Space Systems, Inc. When tested on the second receival, the leak rate was 0.72 cc/min. The bladder was brought to a zero leakage condition by The Boeing Company by adding unsintered Teflon washers between the bladder and the attachment stem surfaces and by sealing the edges of the plies with epoxy/polyamide adhesive.

After vacuum purging the test dewar and upper cryostat, it was observed that the outer two plies of the bladder were against the walls of the test dewar while the remaining plies were in a half-collapsed condition. The initial -423°F helium porosity rate was 9.5 cc/min after the 8 hours and 50 minutes required for reaching equilibrium.

Cyclic Expulsion

Cycles 1 — 5

The first five fill and expulsion cycles were accomplished with very good results. The initial cool down and fill of the test dewar required 18 minutes. The collapse was relatively complete with little indication of ply separation. The effect, if any, of the collapse control device was not visually detectable. Liquid hydrogen was visible between the outer two plies on Cycle No. 5. The helium porosity rate at -423°F was 168 cc/min after Cycle No. 5.

Cycles 6 — 10

The bladder behavior during Cycles 6-10 was much the same as during the first five cycles. Liquid hydrogen was again visible between the outer plies, but filling and expulsion were accomplished with no difficulty. The -423°F He porosity rate after Cycle No. 10 was 171 cc/min.

Cycles 10 — 15

Bladder filling and expulsion behavior was similar to that of the previous cycles. The bladder collapse pattern appeared to be repetitive, but it did not clearly define the collapse control device. The -423°F He porosity rate after Cycle No. 15 was 185.2 cc/min.

Cycles 16 — 20

After Cycle No. 20 it was noted that the outer ply was completely separated from the bladder. The fill and expulsion behavior of the bladder was still quite uniform, but with more liquid hydrogen between the plies. The -423°F He porosity rate was 185.6 cc/min after Cycle No. 20.

Cycles 21 — 25

During these cycles the outer two plies of the bladder were against the walls of the test dewar and liquid hydrogen filling and expulsion took place inside these plies. There was no observed detrimental effect on the cycling of the bladder. The final Helium porosity rates were 412.8 cc/min at -423°F and 52 cc/min at 75°F.

On dissecting the bladder, it was discovered that one leg of the collapse control device was broken. The failure was in the 5 mil Kapton film at the top of the polyurethane rod. This would explain the lack of a well defined collapse pattern during the cyclic testing. There were no tears in any of the other plies which lined up with the broken collapse control device. Ply No. 2 had two tears, one approximately 1.5 inches long and one 0.5 inches long. Plies 3 through 6 had one tear in each ply generally about 0.5 inches long. The tears were randomly distributed over the surface of the bladder and no two tears lined up. Ply No. 9 had a single tear the width of one gore 1.0 inch down from the attachment stem. Ply No. 10 had a horizontal tear through all gores about 1.5 inches down from the attachment stem and had two jagged vertical tears extending from the horizontal tear to the bladder equator.

Bladder 25-MM-12-0

This bladder showed zero porosity to helium at 75°F during the receiving inspection test. Slight ply separation was noted during the vacuum purge of the test dewar and upper cryostat. The initial -423°F helium porosity test was run over a period of 3 hours and 11 minutes with no leakage indicated.

Cyclic Expulsion

Cycles 1 — 5

The bladder collapse was fairly complete but the expulsion phase of Cycle No. 1 was unsuccessful. Liquid hydrogen remained between the plies of the bladder. The test dewar was refilled with liquid hydrogen, but the bladder would not expand when pressurized. The test was terminated when a visual inspection showed severe ply separation with liquid hydrogen between the plies.

When the bladder was dissected, it was found that the adhesive on the MERFAB substrate plies was tacky and tended to stick the MERFAB to itself and the adjacent plies of Mylar. Mylar plies 3, 5 and 6 had no holes or tears. Mylar plies No. 8 and 9 had two small tears and one tear respectively. Plies 11 through 17, five Mylar and two MERFAB, all had a small cut in exactly the same location about 0.75 inches down from the stem assembly. Microscopic examination of the cut on the Mylar plies verified that it was a puncture produced flaw, not a tear. Mylar plies 18 and 20 each had a small patch which coincided with the cut in the inner plies. Mylar ply 18 had a tear across one gore on the equator of the bladder. Mylar ply 20 had a 4 inch long vertical tear in the lower half of one gore. All of the MERFAB plies showed numerous tears, with the length and number of tears in each ply increasing from the inside of the bladder to the outside.

Bladder 25-MM-12-1

This bladder did not meet the receiving inspection requirement of zero helium leakage at 75°F, but had a helium porosity rate of 0.46 cc/min. It was accepted for testing with this leakage because it was deemed that repairs or replacement would be uneconomical. It was judged that the leakage would not significantly affect the test results particularly in the light of the poor performance of its companion bladder 25-MM-12-0.

During the vacuum purge of the test dewar and upper cryostat, ply separation was noted in the bladder to approximately the same extent as for bladder 25-MM-12-0. The helium porosity rate at -423°F was 29.53 cc/min after a stabilization period of 11 hours and 19 minutes.

The 24 hour hydrogen diffusion test was made, but the results of the gas analysis were meaningless due to contamination of the sample through a faulty valve.

Cyclic Expulsion

Cycles 1 — 5

Prior to commencing the initial cycles a visual inspection of the bladder revealed considerable ply separation. Difficulty was experienced in filling the test dewar for Cycle No. 1. Liquid hydrogen flowed into the neck of the test dewar, but the bladder would not collapse at 1 psid. The pressure differential was momentarily raised to 2.5 psid in an unsuccessful attempt to collapse the bladder and then returned to 1 psid. The bladder suddenly collapsed 1 hour and 7 minutes after starting the fill. The total time for filling the test dewar was 1 hour and 13 minutes. The expulsion phase of Cycle No. 1 was accomplished without difficulty although there was some liquid hydrogen visible between the plies. The filling and expulsion for Cycles 2-5 was accomplished very easily without any of the problems encountered in Cycle No. 1. With each cycle, there was progressively more ply separation and lower liquid hydrogen content on filling the test dewar and more liquid hydrogen between the plies of the bladder. During the expulsion phases, the liquid hydrogen could be seen flowing out from between the plies. Shaping of the collapse pattern by the collapse control device was quite evident on Cycle No. 1. The collapse pattern was repeated for the next four cycles, but became progressively less pronounced as the amount of interply inflation increased. The -423°F helium porosity rate was 355 cc/min after Cycle No. 5. Prior to running the helium porosity test it was observed that the outer ply of the bladder was out against the walls of the test dewar and ply separation was quite severe.

Cycles 6 — 10

The bladder behavior during these cycles was much the same as in Cycles 2-5. There was progressively more ply separation, more liquid hydrogen between the plies, and less well defined collapse pattern with each cycle.

The first attempt to run the -423°F helium porosity test after Cycle No. 10 was aborted when the test dewar cracked at the neck. The outer plies of the bladder, one Mylar and one MERFAB, were noted as being torn near the fitting before the bladder was removed from the broken dewar. The bladder was installed in a new test dewar and the -423°F helium porosity rate measured at approximately 4320 cc/min. When the lower cryostat was removed at the end of the test period, it was discovered that the second test dewar had failed in the same area as the first.

Because of the high -423°F helium porosity rate and the probability that the bladder had been damaged by the failure of the two test dewars, the cyclic expulsion tests were terminated. The final 75°F helium porosity rate was 133 cc/min.

Dissection of the bladder revealed that the adhesive used to bond the MERFAB was still tacky as in bladder 25-MM-12-0. All of the MERFAB plies were badly torn with the damage increasing from the inside of the bladder outward. The outermost MERFAB ply, No. 19, was completely shattered, burst at the bottom and pushed up between the two adjacent Mylar plies. The No. 0 Mylar ply, which supported the collapse control device, showed no damage. Mylar ply No. 3 had two 0.5 inch long tears in separate gores, one approximately 2 inches from the top of the bladder, the other 2 inches from the bottom. Mylar ply No. 5 had three small triangular-shaped tears which appeared to have been caused by sticking to Mylar ply No. 6. A piece of Mylar, about 1 inch x 2 inches, torn from Mylar ply No. 6 was stuck to Mylar ply No. 5. There were no flaws in the Mylar plies 8, 9, 11, 12 and 15, but there was a small triangular tear about 0.5 inch long in the top of one gore of ply No. 14. Mylar ply No. 17 contained a pin hole and a vertical tear 1 inch long extending from the stem area. A pin hole, which did not mate with the one in ply No. 17, and three small 0.25—0.50 inch tears were the only damage to Mylar ply No. 18. The outer Mylar ply had a 1-inch tear and two 0.25-inch tears in separate gores at the equator of the bladder and was torn completely around at the stem area. In general, the major damage to the bladder appeared to be caused by the breakage of the test dewars and the tackiness of the MERFAB adhesive.

Bladder 50-X-10-0

Sea-Space, Inc. was unable to develop the required zero helium porosity condition in the first bladder of this type. The bladder was reworked by Sea-Space Systems, Inc. by removing and discarding the outer three plies of No. 3711 film, down to the No. 9 Nomex ply, and replacing them with new barrier plies. It was found on dissecting the bladder after testing by The Boeing Company that five barrier plies had been added instead of three. The reworked bladder reportedly had met the zero helium leakage requirement when shipped from Sea-Space Systems, Inc., but showed a helium porosity rate of 1.71 cc/min when subjected to the receiving inspection test at The Boeing Company. An attempt was made by The Boeing Company to seal the bladder by adding polyurethane adhesive to the ply ends in the attachment stem and closing a small hole near the stem. The leak rate was lowered to 1.3 cc/min. It was apparent at this time from the poor lap bonds and wrinkling of the film, Figure 15, that the S-110 adhesive was not compatible with the No. 3711 film. Since there was neither time nor contractual authorization to find a new adhesive system, the bladder was accepted for testing.

The bladder was quite stiff and hard. It was necessary to compress the bladder diameter at the attachment stem by hand in order to fit the bladder down the neck of the test dewar. The initial $-423^{\circ}F$ helium porosity rate was 37.1 cc/min.

After one-half of the liquid hydrogen had been expelled from the test dewar in preparation for the hydrogen diffusion test, it became very difficult to maintain the required zero pressure differential across the bladder. It was necessary to relieve the pressure on the hydrogen side of the bladder through the hydrogen vent system as well as through the pressure control. The source of the gas pressure or heat-leak could not be located and the test was terminated after 12 hours instead of the specified 24 hours. The analysis of the gas inside the bladder revealed 70% He and 30% H_2.

FIGURE 15 BLADDER 50-X-10-0, SHOWING POOR SEAMS AND FILM WRINKLING

Cyclic Expulsion

Cycles 1 — 5

The collapse of the bladder was incomplete for all cycles and liquid hydrogen was visible between the plies. During expulsion, the liquid hydrogen flowed from between the plies. The bladder acted very stiff, requiring higher pressure differentials for collapse and expulsion than previous bladders. On each cycle the differential pressure across the bladder during expulsion rose gradually as the flow slowly dropped off. Expulsion was terminated at 1 psid. The $-423^{\circ}F$ helium porosity rate was 56.2 cc/min after Cycle No. 5.

Cycles 6 — 10

The actions of the bladder became worse during these cycles. Collapse was less complete, there was more liquid hydrogen between the plies and the pressure differential for expulsion increased more rapidly. The $-423^{\circ}F$ helium porosity rate after Cycle No. 10 was greater than 570 cc/min. The test was terminated because of the poor bladder performance and high helium porosity rate. The $75^{\circ}F$ helium porosity rate was 640 cc/min.

The water expulsion efficiency was determined on this bladder before it was dissected. The dissecting procedure was varied by cutting the bladder around 300° instead of 180° as in the other bladder in an attempt to show the condition of the bladder at the completion of the cyclic expulsion tests, Figure 16. The inner barrier plies of the bladder were collapsed inward and were quite severely wrinkled and compressed. No. 3711 film forms firmly set creases on wrinkling which increased the stiffness of the bladder. The inner plies of the bladder were affected more by this characteristic since the interply inflation limited the compression of the outer plies.

The ply-by-ply examination of the dissected bladder revealed a highly stretched area in Ply No. 1, possibly caused by pressing the film against the

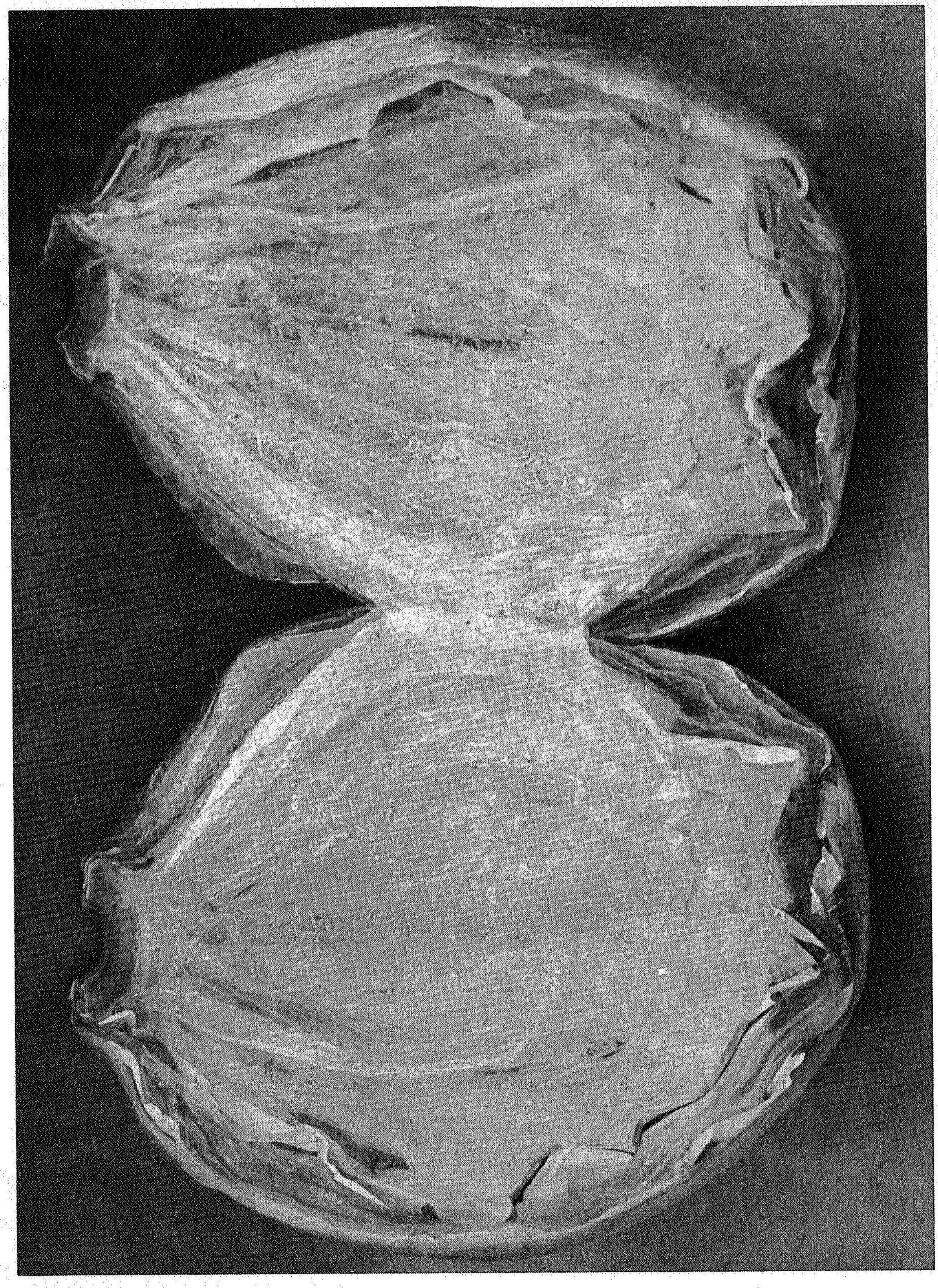


FIGURE 16 BLADDER 50-X-10-0, SHOWING INTERNAL FOLDS AND PLY SEPARATION

helium fill tube, and a 2 inch long tear associated with a very tight fold. Ply No. 2 had no holes but did have about 1 inch of open seam next to a high-stretch area. Plies 4 through 8 had no holes but the lap bond quality was poor. Ply No. 10 had a 45° angle tear across one gore at the equator of the bladder and an open seam 3 inches long at the top of the bladder. Ply No. 11 had no holes or obvious flaws, nor did No. 13. The in-between ply No. 12 had a 0.5 inch long hole in one gore at the equator of the bladder, and the south polar cap consisted of one ply of No. 3711 film and one ply of Mylar. The outer ply No. 14 had 9 small holes adjacent to the stem attachment. The holes in this bladder were not tears but resembled flexural fatigue failures.

Bladder 50-X-10-1

When initially received from Sea-Space Systems, Inc., this bladder showed a 75°F helium porosity rate of 3.9 cc/min and was returned to the vendor. Upon the second receiving inspection test, the bladder had a helium porosity rate of 3.8 cc/min, but was accepted for testing for the reasons outlined for bladder 50-X-10-0. The initial -423°F helium porosity rate was 163.7 cc/min.

Cyclic Expulsion

Cycles 1 — 5

The initial fill of the test dewar required 28 minutes. On Cycles 2—5, the fill phase was decreased to approximately five minutes each. As in bladder 50-X-10-0, the pressure differentials required for bladder collapse and expulsion were higher than any of the previous bladders. The pattern of collapse appeared to be repetitive indicating some degree of collapse control, but the effect was decreased by the stiffness of the bladder, the interply inflation and the poor degree of collapse. The -423°F helium porosity rate was 191.3 cc/min after Cycle No. 5.

Cycles 6 — 10

The bladder behavior was much the same as in Cycles 1—5. Liquid hydrogen was visible between the plies on the fill phase of Cycle No. 7. After Cycle No. 10, the -423°F helium porosity rate was 136 cc/min. Contact of plies in the area of the leak was assumed to be the cause for the decrease in helium porosity rate.

Cycles 11 — 15

The bladder behavior was again as for Cycles 1—5. The -423°F helium porosity rate was 182.2 cc/min after Cycle No. 15.

Cycles 16 — 20

Considerably ply separation was evident during the fill phase of Cycle No. 16. Two hours and 18 minutes were required to effect the first fill. During this time the outer ply was tight against the wall of the test dewar until just prior to collapse. When collapse did occur, it was reasonably complete. The behavior during the remaining cycles was similar to Cycles 2—5. The -423°F helium porosity rate again decreased, this time to a rate of 168.6 cc/min.

Cycles 21 — 25

Prior to Cycle No. 21, an attempt was made to collapse the warm bladder with helium gas on the liquid hydrogen side of the bladder. A pressure differential across the bladder of 3 psid was tried with no effect. Some collapse would occur when the pressure was applied, but the bladder would spring back when the pressure was released. When the test dewar was filled with liquid hydrogen, Cycles 21—25 progressed as Cycles 1—5. The final -423°F helium porosity rate was 187.6 cc/min.

General observation on all the cyclic expulsion runs indicated uniform operation but very stiff behavior of the bladder. The visual ply separation did not appear as severe as in the other bladders tested, indicating that the ply separation was more uniform throughout the bladder or excessive in the inner plies. The gas between the plies evidently was primarily hydrogen since collapse did occur when the bladder was cooled. The final 75°F helium porosity rate was 15.6 cc/min.

5.2 WATER EXPULSION EFFICIENCY TESTS

Water expulsion efficiency tests were conducted on two bladders, 50-X-10-1 which had completed 25 expulsion cycles and 50-X-10-0 which had completed 10 cycles.

Expulsion efficiencies were based on expelled volume versus container volume and expelled volume versus available expulsion volume. The expelled volumes were calculated from measurements of water remaining in the dewar and in the bladder after expulsion.

The following volumes were measured using calibrated glass-ware.

<u>Before Expulsion</u>

a. Container volume, that of the bladder-less dewar filled to the neck, was 12,350 ml.

b. Available expulsion volume, that of the dewar with collapsed bladder and filled to the neck, was 9,840 ml for 50-X-10-1 and 9,350 ml for 50-X-10-0.

c. Unusable volume, that air space in the neck of the dewar containing bladder attachment hardware, was 1,170 ml. This space was filled with water on expulsion and it returned to the dewar upon release of expulsion pressure.

<u>After Expulsion</u>

a. Volume of water remaining trapped between bladder plies was 150 ml for 50-X-10-1 and 250 ml for 50-X-10-0. After expulsion, the bladder was removed from the dewar and the water trapped between plies was collected and measured as it leaked from the bladder. These amounts include a portion of the water from the neck of the dewar which ran down on the release of the expulsion pressure.

b. Volume of water remaining in the bladder-less dewar was 1,050 ml for 50-X-10-1 and 1,250 ml for 50-X-10-0. These amounts include a portion of the water from the neck of the dewar.

Calculations showed that the net volume of water not expelled was 30 ml for 50-X-10-1 and 330 ml for 50-X-10-0. The efficiency based on available expulsion volume was 99.7% for 50-X-10-1 and 96.5% for 50-X-10-0. The efficiency based on container volume was 79.4% for 50-X-10-1 and 73.0% for 50-X-10-0.

Although both bladders leaked sufficiently to trap water between plies, they were able to expel nearly all the available water.

6.0 DISCUSSION

6.1 TASK I — BLADDER FABRICATION

Sea-Space Systems, Inc. encountered one basic problem which was common to all of the bladders fabricated for this program. The lap-type seam with its inherent leak path was very difficult to seal in the attachment stem assembly. The originally proposed method of bonding the end of the plies together with S-110 adhesive was unsuccessful on all bladders and epoxy and polyurethane adhesives had to be added to effect a seal.

The lap-seam produced a similar difficulty at the south polar cap of the bladders with the thicker barrier films, Kapton and No. 3711 film. It was necessary to add a 0.5 inch diameter patch of barrier film at the junctions of several vertical seams at the polar seam in order to seal the ply.

Sea-Space Systems. Inc. S-110 adhesive proved to be a poor selection for use with experimental film No. 3711. Preliminary tests preformed by Sea-Space Systems, Inc. on flat samples yielded good lap bond seams. However, when the same procedures were used to fabricate the barrier plies for the bladders, the solvent in the adhesive caused wrinkling of the film, as previously shown in Figure 16. The lap bond seams which looked and acted good when initially fabricated later lost strength and developed wrinkles and voids.

6.2 TASK II — BLADDER TESTS

Generally, all cryogenic testing progressed as anticipated in the test plan and all equipment functioned well except for the failure of the two test dewars during the testing of Bladder 25-MM-12-1. After the failure of the second dewar, an aluminum retaining ring was replaced with one of stainless steel in order to decrease the stresses induced on the dewar stem by differential thermal contraction. This effectively solved the problem.

The collander chains successfully prevented sealing of the test bladders against the test dewar walls and the trapping of liquid hydrogen. There was no evidence of the collander chains causing tearing or degradation of the bladder. Figures 17 and 18 show the positioning of the collander chains around a bladder collapsed and expanded at ambient temperature. The reason for employing the collander chains instead of a fabric collander was to allow for motion picture coverage of the bladder tests. The motion picture records of the bladder tests proved to be one of the most valuable aids in evaluating the performance of the bladders. The degree and pattern of collapse of the bladders could be accurately judged during the fill phases of the cyclic expulsion tests, and the flow path of the liquid hydrogen could be followed during the expulsion phases. Liquid hydrogen between the plies of a bladder, when it occurred, could be readily detected.

Pertinent comments on the performance of each bladder during testing are as follows:

Bladder 50-K-10-1

The inter-ply inflation which occurred in this bladder during the cyclic expulsion tests was due to helium gas rather than hydrogen. The fact that the amount of inflation increased with each cycle shows that helium gas, which would not be condensed at -423°F, was leaking or permeating through the inner plies of the bladder but was retained by the intact outer ply or plies. This was further verified by the condition of the bladder after the hydrogen diffusion test when the bladder had gross amounts of interply inflation and would not collapse at -423°F.

There was no indication of a controlled collapse pattern on this bladder. This can be attributed to the fact that the control device was bonded on the inner, porous, Nomex ply and probably did not expand into position against the wall of the test dewar before it was rigidized by the cryogenic temperature. The inherent stiffness of the Nomex material would also contribute to a mislocation of the collapse control device.

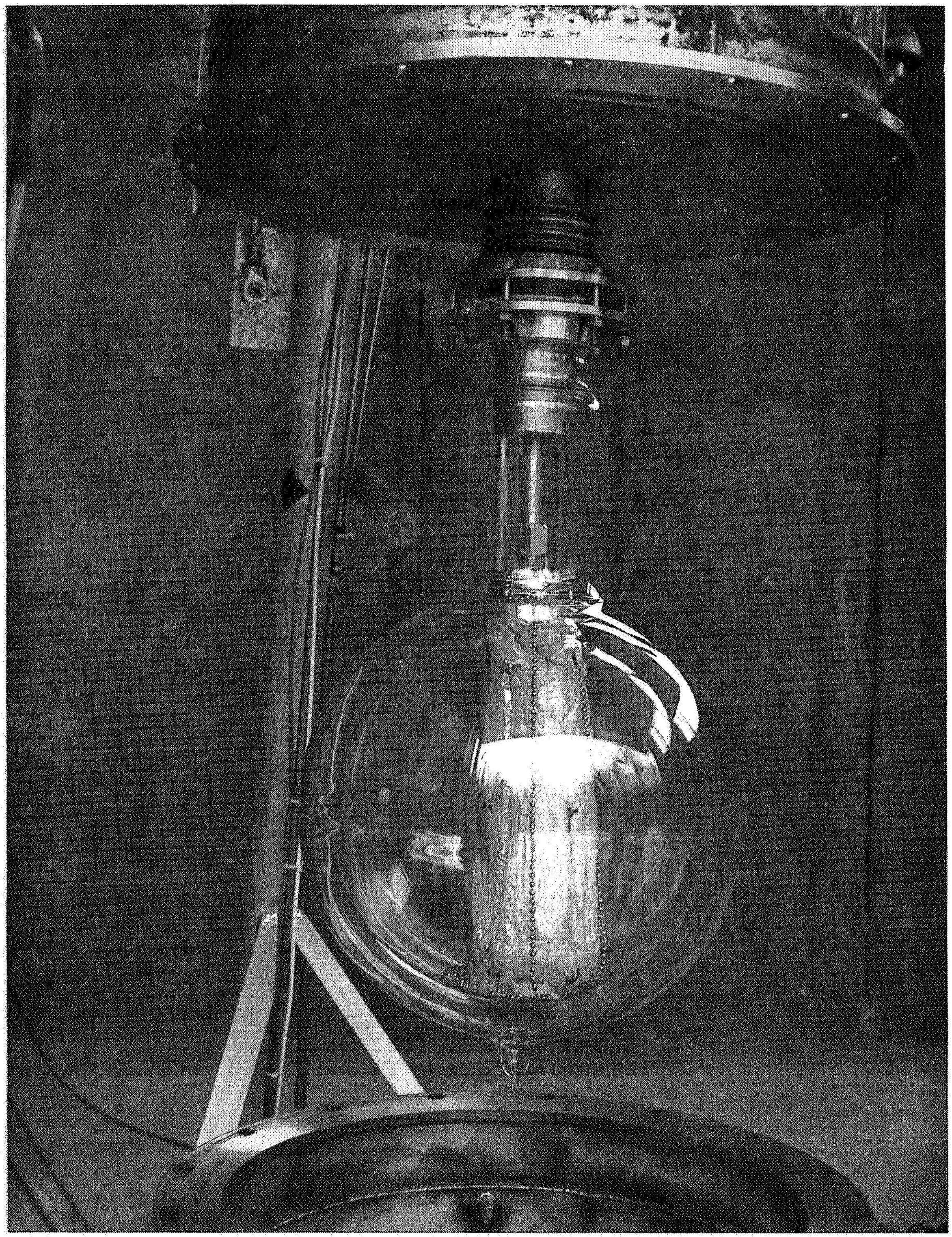


FIGURE 17 COLLAPSED BLADDER (75°F)

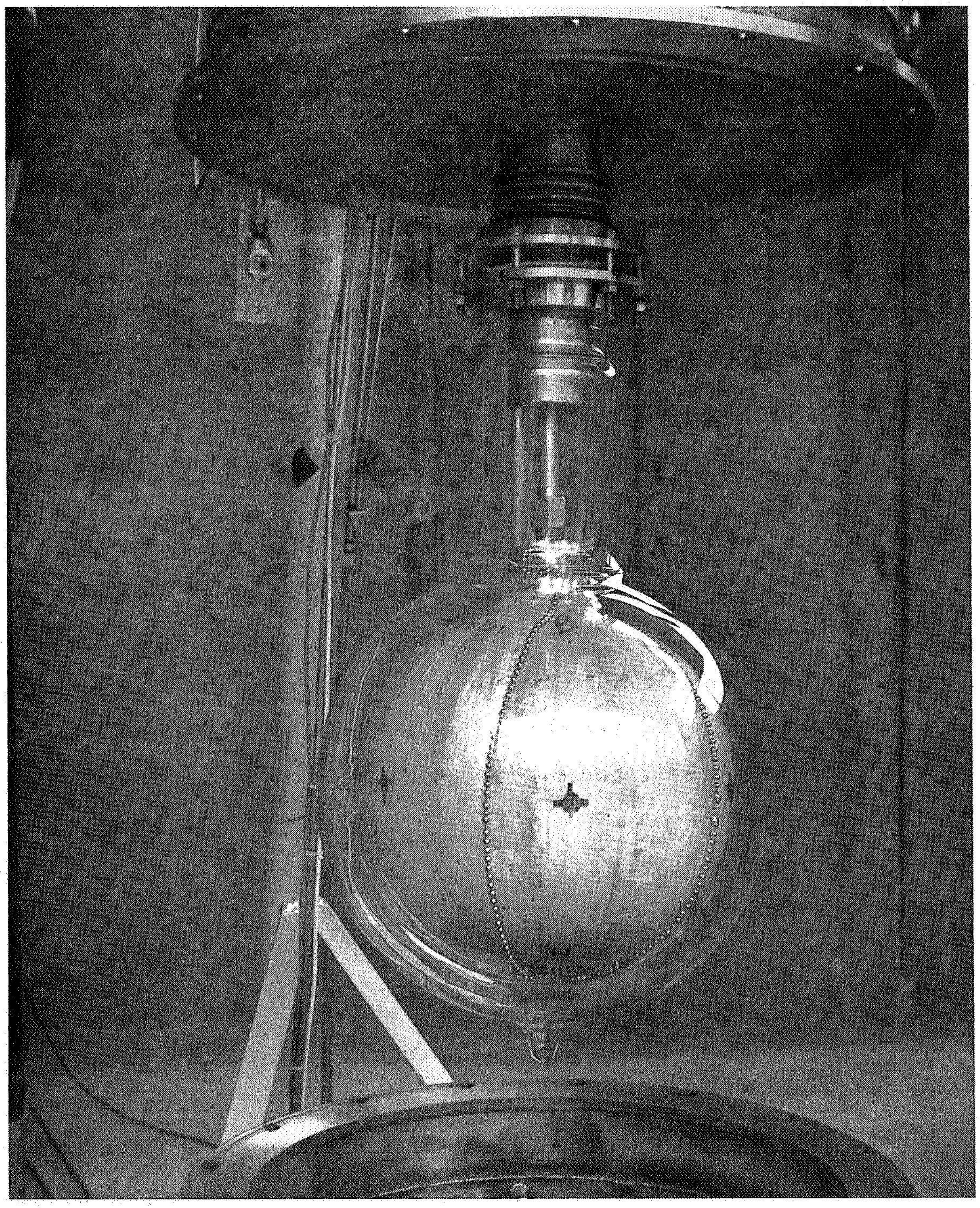


FIGURE 18 EXPANDED BLADDER (75°F)

Bladder 25-M-10-0

The rapid failure of this bladder is difficult to explain. The presence of liquid hydrogen between the plies after the hydrogen diffusion test showed that the outer plies of this bladder failed very early in the testing. The first five cyclic expulsions visibly increased the damage to the outer plies and the second series of cyclic expulsions extended the damage into the inner plies. Eight of the inner plies were torn in the same location near the top of the bladder, indicating that the pattern of collapse from the bottom up developed a high stress concentration or a deep fold at that point.

Bladder 25-M-10-1

This bladder, like 25-M-10-0, failed in the outer plies during the first five expulsion cycles. Thereafter, all similarity ceased. Bladder 25-M-10-1 functioned well through the required 25 expulsion cycles even though the outer two plies had completely failed and the liquid hydrogen flowed in and out between the plies. When the bladder was dissected, two plies, Nos. 7 and 8, were still intact and the other inner plies had only small randomly distributed tears. The collapse control device was only partially functional due to one broken leg, but it did appear to operate to some extent since the bladder did not collapse from the bottom up and the collapse pattern was repetitive.

Bladder 25-MM-12-0

This bladder would not expel the liquid hydrogen on the first cyclic expulsion test. The initial filling of the test dewar was fairly complete, but then the outer two plies of the bladder failed and the bladder would not expand when pressurized. The presence of a puncture type hole aligned through five of the barrier plies and patches in the same area on the outer two barrier plies would indicate that the bladder had been damaged in final assembly and only the outer two plies had been repaired. The failure of the outer two plies and the existence of an in-line leak path through the next five barrier plies still does not explain why the bladder would not expel since the inner three Mylar barrier plies were intact. One possible explanation would be that the seal in the stem attachment area failed and allowed a flow-path around the intact plies.

Bladder 25-MM-12-1

As in bladder 50-K-10-1, difficulty was encountered in collapsing this bladder for the cyclic expulsion tests following the hydrogen diffusion test. However, in this bladder, the interply gas was hydrogen and collapse did occur when the bladder was cooled to $-423^{\circ}F$. As in all the Mylar bladders, the outer plies failed during the first five cyclic expulsions allowing liquid hydrogen to flow between the plies. It appeared that ply failure progressed inward as more cycles were added. This was verified by the dissection of the bladder following testing, but it was also discovered that the bladder was failing in the inner plies due to the tacky S-110 adhesive.

The collapse control device on this bladder functioned well and the bladder probably would have lasted for at least another five cycles if it had not been damaged by the breaking of the test dewars.

Bladder 50-X-10-0

The continued high pressure on the liquid hydrogen side of this bladder during the hydrogen diffusion test cannot be explained entirely. Both of the cryostats indicated proper liquid levels which would preclude extraneous heat leaks. The bladder should have been at $-423^{\circ}F$ after having been immersed for 12 hours in liquid hydrogen. The helium gas flow into the bladder was negligible and it was also precooled to $-423^{\circ}F$. The observed effect could have occurred if liquid hydrogen had flowed into the bladder plies and vaporized. This would expand the outer plies of the bladder and drive liquid hydrogen out of the dewar into the vent system. This explanation would be valid if a source of energy to vaporize the liquid hydrogen in the bladder could be defined.

The relatively small number of expulsion cycles (10) accomplished by this bladder may be attributed to the poor strength of the lap bonds and the over-all stiffness of the bladder. The tear damage in the neck region of the outer ply may have been caused immediately or latently by the stresses induced by compressing the bladder to install it in the test dewar. The minor number and size of the tears in the bulk of the barrier plies would not have caused failure of the bladder had it not been for the open seams.

The poor collapse and expulsion behavior of the bladder can be attributed to interply inflation and the stiffness of the bladder. The dissected bladder showed that the interply inflation had caused severe compression of the inner plies during some of the fill phases and yet the bladder collapse, as viewed from the outside, was rather poor for most cycles. The stiffness of the No. 3711 film, either inherent or induced by exposure to the solvents in the adhesive, combined with the stiffness of the Nomex substrate plies resulted in a bladder which did not flex readily under the 1 psid limit of this program.

Bladder 50-X-10-1

The behavior of this bladder during the cyclic expulsion tests was very much like bladder 50-X-10-0. The bladder operation was equally stiff requiring the total allowed pressure differential of 1 psi for collapse and expulsion, and there was liquid and gaseous hydrogen between the plies. The ability of this bladder to function through 25 expulsion cycles, while its companion bladder failed at 10 cycles, is a clear indication that control of the collapse pattern decreases bladder damage and increases bladder life.

7.0 CONCLUSIONS

The following major conclusions can be drawn from the test data of this program:

1. The outward expulsion mode, with the liquid hydrogen external to the bladder, is no more effective in preventing interply inflation of polymeric bladders by hydrogen or helium gas than the inward expulsion mode.

2. The No. 3711 experimental polyester film showed the best resistance to tearing at -423°F and the greatest cyclic expulsion endurance. The Kapton film appeared to be second in cryogenic tear resistance, but could not be fully evaluated because of the excessive ply separation of the bladder.

3. Increased cyclic expulsion endurance was indicated for bladders containing a collapse control device. However, the effectiveness of the device was decreased by the stiffness and interply inflation of the test bladders.

4. The results of the hydrogen diffusion tests were inconclusive insofar as the analysis of the gas inside the bladders was concerned. The initial helium porosity of all of the test bladders at -423°F was such that the hydrogen gas detected inside the bladders after the diffusion test could have penetrated by leakage as well as by diffusion.

   The hydrogen diffusion tests did show that the permeability of barrier ply material to hydrogen and helium must be controlled before reliable liquid hydrogen expulsion bladders can be developed. Bladder 50-K-10-1 was rendered completely inoperative by interply inflation with helium gas, and bladders which had interply inflation with hydrogen gas had to be cooled to -423°F before they would function properly.

5. The expulsion efficiency test as conducted with ambient temperature water is not a valid evaluation procedure for cryogenic bladders. The two bladders tested, one of which had a high helium leak rate, were equally effective in expelling the water.

The following secondary conclusions can be drawn from the bladder fabrication and test data:

1. The lap-type seam is not compatible with the type of attachment stem assembly employed in this program. The major problem encountered in fabricating the test bladders was obtaining zero helium leakage in the attachment stem area. In addition, much of the $-423^{\circ}F$ helium porosity encountered in the test runs was probably due to premature failure of the adhesive in the stem area.

2. Sea-Space Systems, Inc. S-110 adhesive is not compatible with experimental film No. 3711 evaluated in this program.

3. The residual tackiness of the Sea-Space Systems, Inc. S-110 adhesive caused premature failures of bladders 25-MM-10-0 and 25-MM-10-1.

4. Substrate plies of 2 mil Nomex are too rigid for bladders with the dimensions of those tested in this program. The stiffness and incomplete collapse patterns of bladders 50-K-10-1, 50-X-10-0, and 50-X-10-1 must be attributed in some degree to the stiffness of the substrate plies.

5. Barrier plies of 0.25 mil Mylar film do not have sufficient wrinkle or tear resistance at $-423^{\circ}F$ for use in liquid hydrogen positive expulsion bladders.

8.0 RECOMMENDATIONS

It is recommended that future development programs for liquid hydrogen positive expulsion bladders forego testing of bladders per se until such time as the basic material problem of gas permeation through the bladders can be solved. Thin metal films applied to the barrier film material by plating or laminating should be evaluated as gas permeation barriers. Kapton and No. 3711 film should be used as the barrier ply materials initially, with any new polymeric film being added only after evaluation by the Twist-Flex test (Reference 4). Composite barrier ply films should also be evaluated by the Twist-Flex test with hydrogen and helium permeation being measured before and after the test.

After the development of impermeable composite barrier ply films, the bladder evaluation tests of this program should be repeated, but with the following modifications:

1. The construction of the bladders plies should be changed to provide a flat continuous surface in the stem attachment area.

2. The bladders should be attached or restrained at both ends and should be tested in the inward expulsion mode.

3. A collapse control device should be included in the bladder system but not as an integral part of the bladder. A separately installed device can be designed for greater effectiveness than one built into the bladder.

9.0 REFERENCES

1. "Development of Positive Expulsion System for Cryogenic Fluids", SSD-TRD-62-14, Contract AF 33(616)6930, Beech Aircraft Corp., Boulder, Colorado, May 1962.

2. Hoggatt, J. T., "Development of Liquid Oxygen Positive Expulsion Bladders", NASA CR-72418, June 1968.

3. Pope, D. H. and Pennes, J. E., "Development of Cryogenic Positive Expulsion Bladders", NAS CR-72115, January 1968.

4. Lark, R. F., "Cryogenic Positive Expulsion Bladders", NASA TM X-1555, April 1968.

DISTRIBUTION LIST

		COPIES
National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135		
Attention:	Contracting Officer, MS 500-210	1
	Liquid Rocket Technology Branch, MS 500-209	8
	Technical Report Control Office, MS 5-5	1
	Technology Utilization Office, MS 3-16	1
	AFSC Liaison Office, MS 4-1	2
	Library	2
	Office of Reliability & Quality Assurance, MS 500-203	1
	E. W. Conrad, MS 100-1	1
National Aeronautics and Space Administration Washington, D.C. 20546		
Attention:	Code MT	1
	RPX	2
	RPL	2
	SV	1
	N. J. Mayer, RV-2	1
	A. O. Tischler, RP	1
	B. Achhammer, RRM	1
Scientific and Technical Information Facility P.O. Box 33 College Park, Maryland 20740		
Attention:	NASA Representative Code CRT	6
National Aeronautics and Space Administration Ames Research Center Moffett Field, California 94035		
Attention:	Library	1

COPIES

National Aeronautics and Space Administration
Flight Research Center
P. O. Box 273
Edwards, California 93523
Attention: Library 1

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771
Attention: Library 1

National Aeronautics and Space Administration
John F. Kennedy Space Center
Cocoa Beach, Florida 32931
Attention: Library 1

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365
Attention: Library 1

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas 77001
Attention: Library 1

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812
Attention: Library 1
Keith Chandler, R-P&VE-PA 1
Harry L. McDaris, T-T/TR-ST 1
John T. Schell, R-P&VE-NMR 1
Wilbur A. Riehl, R-P&VE-MC 1

National Aeronautics and Space Administration
Western Operations Office
150 Pico Boulevard
Santa Monica, California 90406
Attention: Library 1

COPIES

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103
Attention: Library 1
D. D. Lawson 1
Howard Stanford 1

Office of the Director of Defense Research & Engineering
Washington, D. C. 20301
Attention: Dr. H. W. Schulz, Office of Asst. Dir. 1
(Chem. Technology)

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314 1

RTD(RTNP)
Bolling Air Force Base
Washington, D. C. 20332 1

Arnold Engineering Development Center
Air Force Systems Command
Tullahoma, Tennessee 37389
Attention: AEOIM 1

Advanced Research Projects Agency
Washington, D. C. 20525
Attention: D. E. Mock 1

Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base,
Dayton, Ohio
Attention: D. L. Schmidt,
Code ASRCNC-2 1

Air Force Missile Test Center
Patrick Air Force Base, Florida
Attention: L. J. Ullian 1

Air Force Systems Command (SCLT/Capt. S. W. Bowen)
Andrews Air Force Base
Washington, D. C. 20332 1

Air Force Rocket Propulsion Laboratory
Edwards, California 93523
Attention: J. E. Branigan, RP-R-PT 1
RPR 1
RPM 1

	COPIES
Air Force FTC (FTAT-2) Edwards Air Force Base, California 93523	1
Attention: Col. J. M. Silk	1
Air Force Office of Scientific Research Washington, D. C. 20333 Attention: SREP, Dr. J. F. Masi	1
Office of Research Analyses (OAR) Holloman Air Force Base, New Mexico 88330 Attention: RRRT	1
Maj. R. E. Brocken, Code MDGRT	1
U. S. Air Force Washington 25, D. C. Attention: Col. C. K. Stambaugh, Code AFRST	1
Commanding Officer U. S. Army Research Office (Durham) Box CM, Duke Station Durham, North Carolina 27706	1
U. S. Army Missile Command Redstone Scientific Information Center Redstone Arsenal, Alabama 35808 Attention: Chief, Document Section	1
Dr. W. Wharton	1
Bureau of Naval Weapons Department of the Navy Washington, D. C. Attention: J. Kay, Code RTMS-41	1
Commander U. S. Naval Missile Center Point Mugu, California 93041 Attention: Technical Library	1
Commander U. S. Naval Ordnance Test Station China Lake, California 93557 Attention: Code 753	1
W. F. Thorm, Code 4562	1

	COPIES
Commanding Officer Office of Naval Research 1030 E. Green Street Pasadena, California 91101	1
Director (Code 6180) U. S. Naval Research Laboratory Washington, D. C. 20390 Attention: H. W. Carhart	1
Picatinny Arsenal Dover, New Jersey Attention: I. Forsten, Chief Liquid Propulsion Laboratory	1
U. S. Atomic Energy Commission Technical Information Services Box 62 Oak Ridge, Tennessee Attention: A. P. Huber, Code ORCDP Box P	1
Air Force Aero Propulsion Laboratory Research & Technology Division Air Force Systems Command United States Air Force Wright-Patterson AFB, Ohio 45433 Attention: APRP (C. M. Donaldson)	1
R. Quigley	1
Aerospace Corporation P. O. Box 95085 Los Angeles, California 90045 Attention: Library-Documents	1
W. Heller	1
ARO, Incorporated Arnold Engineering Development Center Arnold AF Station, Tennessee 37389 Attention: Dr. B. H. Coethert, Chief Scientist	1
Beech Aircraft Corporation Boulder Facility Box 631 Boulder, Colorado 80301 Attention: Douglas Pope	1

	COPIES
Bell Aerosystems, Inc. Box 1 Buffalo, New York 14205 Attention: Library	1
Bendix Systems Division Bendix Corporation Ann Arbor, Michigan Attention: John M. Bureger	1
Chemical Propulsion Information Agency Applied Physics Laboratory 8621 Georgia Avenue Silver Springs, Maryland 20910	1
Curtiss-Wright Corporation Wright Aeronautical Division Woodridge, New Jersey Attention: C. Kelley	1
Douglas Aircraft Company, Inc. Santa Monica Division 3000 Ocean Park Blvd. Santa Monica, California 90405 Attention: Library	1
Fairchild Stratos Corporation Aircraft Missiles Division Hagerstown, Maryland Attention: J. S. Kerr	1
General Dynamics/Astronautics P. O. Box 1128 San Diego, California 92112 Attention: Library & Information Services (128-00)	1
Convair Division General Dynamics Corporation P. O. Box 1128 San Diego, California 92112 Attention: Mr. W. Fenning Centaur Resident Project Office	1
General Electric Company Re-Entry Systems Department P. O. Box 8555 Philadelphia, Pennsylvania 19101 Attention: F. E. Schultz	1
General Electric Company Flight Propulsion Lab. Department Cincinnati, Ohio Attention: D. Suichu	1

	COPIES
Grumman Aircraft Engineering Corporation Bethpage, Long Island, New York Attention: Joseph Gavin	1
ITT Research Institute Technology Center Chicago, Illinois 60616 Attention: C. K. Hersh, Chemistry Division	1
Lockheed-California Company 10445 Glen Oaks Blvd. Pacoima, California Attention: G. D. Brewer	1
Lockheed Propulsion Company P. O. Box 111 Redlands, California 92374 Attention: Miss Belle Berlad, Librarian	1
Lockheed Missiles & Space Company Propulsion Engineering Division (D55-11) 1111 Lockheed Way Sunnyvale, California 94087	1
Marquardt Corporation 16555 Saticoy Street Box 2013 — South Annex Van Nuys, California 91404 Attention: Librarian	1
Martin-Marietta Corporation Martin Division Baltimore 3, Maryland Attention: John Calathes (3214)	1
McDonnell Aircraft Corporation P. O. Box 6101 Lambert Field, Missouri Attention: R. A. Herzmark	1
North American Aviation, Inc. Space & Information Systems Division 12214 Lakewood Boulevard Downey, California 90242 Attention: Technical Information Center, D/096-722 (AJOI)	1
Northrop Space Laboratories 1001 East Broadway Hawthorne, California Attention: Dr. William Howard	1
Purdue University Lafayette, Indiana 47907 Attention: Technical Librarian	1

COPIES

Radio Corporation of America Astro-Electronics Division Defense Electronic Products Princeton, New Jersey Attention: S. Fairweather	1
Republic Aviation Corporation Farmingdale, Long Island, New York Attention: Dr. William O'Donnell	1
Rocket Research Corporation 520 South Portland Street Seattle, Washington 98108	1
Rocketdyne Division of North American Aviation, Inc. 6633 Canoga Avenue Canoga Park, California 91304 Attention: Library, Department 596-306	1
Rohm and Haas Company Redstone Arsenal Research Division Huntsville, Alabama 35808 Attention: Librarian	1
Space-General Corporation 777 Flower Street Glendale, California Attention: C. E. Roth	1
Stanford Research Institute 333 Ravenswood Avenue Menlo Park, California 94025 Attention: Thor Smith	1
Lockheed Missiles & Space Company P. O. Box 504 Sunnyvale, California Attention: Technical Information Center	1
Thiokol Chemical Corporation Alpha Division, Huntsville Plant Huntsville, Alabama 35800 Attention: Technical Director	1
Thiokol Chemical Corporation Reaction Motors Division Denville, New Jersey 07834 Attention: Librarian	1
Thiokol Chemical Corporation Redstone Division Huntsville, Alabama Attention: John Goodloe	1

	COPIES
TRW Systems, Incorporated 1 Space Park Redondo Beach, California 90200 Attention: STL Tech. Lib. Doc. Acquisitions	1
LTV Astro Division P. O. Box 6267 Dallas, Texas 75222 Attention: Library	1
United Aircraft Corporation Corporation Library 400 Main Street East Hartford, Connecticut 06118 Attention: Library	1
United Aircraft Corporation Pratt & Whitney Division Florida Research & Development Center P. O. Box 2691 West Palm Beach, Florida 33402 Attention: Library	1
United Aircraft Corporation United Technology Center P. O. Box 358 Sunnyvale, California 94088 Attention: Librarian	1
Air Force Material Laboratory Wright-Patterson AFB, Ohio 45433 Attention: C. C. Roach S. Litvak	1 1
Sea-Space Systems, Inc. 1754 S. Crenshaw Blvd. Torrance, California Attention: D. Struble	1
G. T. Schjeldahl Co. Northfield, Minn Attention: Library	1
Sandia Corporation P. O. Box 969 Livermore, California 94550 Attention: Technical Library (RPT) H. Lucas	1 1

	COPIES
National Aeronautics & Space Administration George C. Marshall Space Flight Center Huntsville, Alabama 35812 Attention: Leon J. Hastings, Code R&PVE-PTF	1
Department of the Air Force Air Force Materials Laboratory (AFSC) Wright-Patterson Air Force Base, Ohio 45433 Attention: R. E. Headrick, MANE	1